KU LEUVEN

FACULTY OF ECONOMICS AND BUSINESS

# PUBLIC-PRIVATE PARTNERSHIP PROCUREMENT: GAME-THEORETIC STUDIES OF THE TENDER PROCESS

Dissertation presented to obtain the degree of Doctor in Business Economics

by

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Dear reader of this dissertation, I am grateful for your interest in this research project. Many people directly and indirectly contributed to its content. Unfortunately, it is only my name that is printed on the cover. This work has been the result of people inspiring me. To all of you, I wish that you may also experience this incredible support, the hunger to creativity an the foolishness of realizing your dreams.

**Dennis De Clerck**

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# Abstract

A Public-private partnership (PPP) is a settlement between a public party and a contractor or private sector consortium to engage in a long-term contractual agreement for designing, building, operating and/or maintaining capital intensive projects, while trying to attain value for money. PPPs are globally gaining importance in the construction industry. The risk transfer from the contracting government towards the private entity has important repercussions on the tender. Contractors need to carefully prepare the bid proposal and need to make an assessment of the project risk. These investigations require expensive investment efforts that might go down the drain in case the bidder loses the tender. The competitive context might be an inhibitor for players to participate in the high-risk tender process. Besides, it is in the social interest that public entities select consortia capable of performing the project with outstanding quality, yet at a reasonable price. Therefore, governments are currently seeking for mechanisms to increase competition. A literature review on the academic PPP field did not bring solace into how to deal with these challenges and theoretical models are lacking.

This dissertation develops a theoretical procurement model that imitates the PPP market by means of a bi-level experimental single-project and multi-project bidding setting. At the lower level, the bidders are heterogeneous in their experience, so that more experienced contractors have a cost advantage and, additionally, they are able to more accurately estimate the project cost.

A contractor's project strategy is composed of two elements. On the one hand, the pre-tender investment reflects the monetary effort a contractor is willing to undertake to prepare the proposal. The investments could lead to cost effective innovations and to the capability of more precisely estimating the project cost. On the other hand, the targeted mark-up consists of a risk premium and a profit margin. The Bayesian Nash equilibrium and Markov perfect equilibrium of the games are heuristically approximated by best response mechanisms. At the upper level, the impact of governmental contractual policies on the bidding equilibrium is investigated. The computer experiments are subsequently triangulated with the findings from a laboratory experiment and with views from practitioners in order to gain understanding of the complex international PPP field.

The government impersonates the architect of the tendering process and should aim for a clear funneling principle with respect to the number of bidders to invite. In order to create a levelled playing field that guarantees competitive forces in the long run, additional incentive mechanisms are necessary to close the gap between incumbents and entrants. In this vein, the introduction of a partial reimbursement of the bid cost in complex project settings is proven to add value. Furthermore, the public entity could aim to reduce non-value adding pre-tender costs by means of standardized contracts. Finally, a project pipeline effectively stirs up the enthusiasm of the consortia rendering a lower government procurement cost.

The results of the dissertation underline the importance of the assessment of the project's complexity and the competitive environment. Additionally, consortia could benefit from making the pre-tender investment efforts transferable to future project opportunities. However, the interplay of project risk, the competitive forces and the contractual setup makes it a daunting field of operation and the disheartening winner's curse amplifies the adagio "look before you leap into marriage".

# Contents

# Chapter 1 Introduction

This dissertation deals with the study of the procurement mechanism of high-risk projects. Traditionally, governments aimed to build economic and social public infrastructures by selecting a low-cost contractor that executes the project without having any further obligations. Contractors just needed to account for the project-specific contingencies, but incurring a risk premium sufficed to mitigate these risks. This is in contrast to high-risk projects that would require careful preparation of the project proposal and a thorough identification and assessment of the risks. One of the most recent and most innovative kinds of these prototype high-risk contracts are public-private partnerships (PPPs) and these type of projects consequently define the focus of this dissertation.

## 1.1 Definition of a public-private partnership

Public-private partnerships have appeared on the scene as a cutting-edge long-term contractual arrangement between a private contractor and the government. The concept is widely known around the world, but there is quite some disagreement about its content. Wettenhall (2010) claims that PPPs have been developed from the earliest civilizations onwards, but that might be somehow misleading. The PPP acronym itself has been used since the seventies and got a buzzword status in the nineties with the rise of the importance of the Public Finance Initiative (PFI) in the United Kingdom for social and economic environment renewal under surveillance of the public expenditures (Bovaird, 2010).

PPPs were believed to guarantee greater value for money for the government compared to traditional public contracting, because the transfer of the design, operation and maintenance responsibilities and risks towards the private consortium or special purpose vehicle (SPV) generates synergies and efficiency gains. Since they have seen the daylight, PPPs have gained importance and their number has proliferated. The PPP landscape is wide which is proven by the variety in definitions (e.g., Van Ham and Koppenjan 2001, Hodge and Greve 2007, Wettenhall 2010). Yang et al. (2010) attribute this to the plethora of contract types: build-own-operate-transfer, joint ventures, sale-and-lease-back, design-build-maintain, et cetera. Besides, legal requirements may provoke different interpretations of the concept. For the purpose of this dissertation, all the ornaments and often country- or sector-specific features are removed.

*A public-private partnership is defined as a settlement between a public party and a private sector consortium to engage in a long-term contractual agreement for designing, building, operating and/or maintaining capital intensive projects, while trying to attain value for money by the appropriate allocation of risk.*

A PPP has been a popular means to perform long-term public investments. Hodge and Greve (2007) describe PPPs as a mega credit card for governments, but other authors like Kumaraswamy et al. (2007) underline drivers that are based on efficiency gains and value for money in so-called second generation PPPs. Globally, the number of PPPs and the amount of money invested in this contracting method had an upward trend in the previous decades (EPEC 2012). This trend is also coupled with the observation by Flyvbjerg et al. (2004) that construction projects grow larger, making the societal value of the project surge. The global financial crisis resulted in a shrinkage of the European market, but the PPP market has been slightly recovering since 2012 (EPEC 2015). Not only developed countries increasingly adopt PPPs, but also in developing countries, private finance for public projects in the primary sector has gained importance, especially in the South Asian, the Latin American and the Caribbean regions.

According to the figures from The World Bank Group, the energy sector and the telecommunications sector absorb the most significant shares of the money that has been spent in the developing countries since 1990.

## 1.2 Problem statement

Because of the long-term feature, often covering a timespan of thirty years, PPPs are not always a bed of roses. Typical textbook cases that reveal time overruns, cost escalations or revenue shortfalls in for instance the Eurotunnel project (Flyvbjerg et al. 2009) and the Sydney New Southern Rail project (Ng and Loosemore 2007) underline the possible disastrous outcomes for society and form another argument to put an emphasis on carefully planning these risky projects (Zwikael and Sadeh 2007) and one should look before leaping into marriage (De Clerck et al. 2012).

After an initial prequalification of the interested consortia by the government, qualified concessionaires are invited for the tender. Due to the complex project nature and the high societal value that is at stake, financial performance requirements and high quality standards are important challenges one needs to face. Therefore, contractors ought to prepare a qualitative bid proposal to submit to the contracting government. The preparation of this proposal is costly (e.g., consultancy cost, working cost, design cost) and the risk of not being awarded the contract is empirically claimed to be a burden for contractors (Ahadzi and Bowles 2004, Carrillo et al. 2008, KPMG 2010). Dudkin and Välilä (2005) report transaction costs of two to three percent of the total contract value. More recent empirical evidence by KPMG (2010) reports average research costs of 1.5% to 2% of the total project cost. Due to the complexity, the high contingencies and the bidding costs, policy makers often argue that the market is too narrow in some jurisdictions, like in Australia, New Zealand or western European countries where often only two or three private entities show interest in particular high-risk PPPs.

In order to open up the playing field and to incentivize the consortia to submit qualitative bid proposals and for possible entrants to penetrate the market, policy makers are endowed to seek for feasible ways to substantiate the PPP market's attractiveness. A recent KPMG report (2010) concludes with a set of guidelines to improve the efficiency of the PPP process and to reduce the bid costs which would in its turn stimulate the PPP market's allure. Two of the suggested policies are investigated in detail in this dissertation. Firstly, public institutions sometimes introduce reimbursements to (some of) the losing bidders for the incurred pre-tender bid preparation efforts. However, there is no global agreement on the magnitude of these compensations. Moreover, and supported by empirical evidence in Canada for instance, a pipeline of projects could increase the eagerness of consortia to enter and stay in the PPP market of a particular country (KPMG 2010). This pipeline reduces a consortium's risk of being unsuccessful, because instead of putting all one's eggs in one basket, a consortium can spread out its investments across different projects and it can offset former losses in future tenders.

Consequently, this dissertation presents a theoretical framework that models the procurement procedure and that grasps the main peculiarities of the PPP agreements. The purpose of the model is to get insights into the equilibrium bidding behavior of the contractors or consortia and into how the project characteristics influence the dynamics of the bidding behavior. Subsequently, we are able to assess how the government, as a decision maker, may shape the strategic choices of the contractors.

The policies that we are mainly interested in are:

- The number of players that are invited for the tender;
- The fraction of the investment cost that is reimbursed to the losing bidders;
- The construction of a pipeline of projects.

## 1.3 Outline of the dissertation

The remainder of the dissertation is structured as follows. In Chapter 2, we introduce the main lexicon of the PPP field and we give a detailed overview of the state-of-the art of this highly innovative way of contracting. In this vein, we want to give an overview of the current research trends and underline the academic opportunities within the operations research field. Moreover, this chapter positions the dissertation within the infrastructure bidding literature. The more specific methodology-focused literature of the subsequent topics is discussed in the respective chapters.

Chapter 3 covers the model and assumptions of the overall procurement setting. The aim of the research project was to give a realistic representation of the real-life project environment, which distinguishes our work from the contemporary auction literature. Noteworthy is the fact that we include uncertainty in the project outcome and that we have introduced asymmetries in the bidders' profiles. Moreover, the strategies that contractors need to determine have two dimensions. Firstly, they make an investment decision that reflects how much effort they are willing to put in knowledge acquisition that results in an uncertainty decrease and in a cost reduction. The second dimension concerns the mark-up that is applied to the estimated cost. Combining both choices for each of the projects under study determines the player's strategy.

Chapter 4 reports the results of the study of a single-project environment. For a given vector of experience levels that reflects the familiarity with this particular type of projects in this particular jurisdiction, the bidding equilibrium is approximated. The pay-off calculations rely on a simulation approach that allows flexibility in the modelling and that speeds up the experiments. Two approximation algorithms are presented. On the one hand, the Nash equilibrium method explicitly computes the pay-offs for each strategy profile and derives a Bayesian Nash equilibrium in unique strategies, but only considers a discrete number of strategies for each player. On the other hand, a strategy game algorithm studies a larger set of strategies and finds the best response for a particular player after narrowing down the strategy space of the opponents. The chapter also studies whether a fractional reimbursement of the investment efforts could level the playing field.

Chapter 5 and Chapter 6 extend the single-project environment towards a multi-project setting, which is referred to as the project pipeline. Due to synergetic effects, contractors may use past experience from won projects in future opportunities. Usually, these pipelines have a limited nature, because of the large contingencies and the long timespan of the contractual agreements and because of the fact that governments and their agendas regularly change. Chapter 5 considers a situation in which the contractors make an *ex ante* bidding decision. Tendering processes are often overlapping and contractors need to spread their research budget over the pipeline of projects while they do not know in advance whether they will win or lose a project early in the pipeline. This is in contrast to Chapter 6, which allows contractors to modify their actions along the pipeline. In practice, the decision process has a mixed nature of both an *ex ante* as well as a sequential consideration so a study of these two extreme situations could guide us towards managerial insights on the effect of a pipeline of projects. Moreover, both chapters differ in their equilibrium solution concept. While the *ex ante* model of Chapter 5 studies a Bayesian Nash equilibrium, Chapter 6 introduces the Markov perfect equilibrium concept. Both chapters also differ in their algorithmic set-up. Chapter 5 follows the strategy game methodology of Chapter 4 with the respective pay-off simulation. During the course of the research project, we succeeded in exactly defining the pay-offs for a given set of players and a given set of actions. Therefore, Chapter 6 exactly calculates the expected pay-offs under the assumption of Gaussian cost probability distributions. A best response heuristic is the implemented equilibrium approximation method for the sequential model.

As data are scarce in this highly competitive environment, it has been a challenge to validate the theoretical findings and to get insights into human aspects of the procurement process. Eventually, we succeeded in setting up a research network of contractors, public institutions, advisory firms and lawyers that were able to give feedback on our findings. Some important aspects of this triangulation process can be found in Chapter 7. Additionally, we have translated some of the scenarios into a laboratory experiment. 180 students were invited to participate in a bidding experiment that mimics the computer experiments. Chapter 7 summarizes the set-up and findings. The study confirms the majority of the predicted dynamics that were identified in the computer experiment, but it also reveals that the subjects deviate from the social optimum, which has mainly its roots in the participants' consistent underbidding behavior.

Finally, Chapter 8 concludes the dissertation with a summary of the conclusions and an overview of future research opportunities.

Four appendices are added as additional relevant material. Appendix A lists the notation and the abbreviations and definitions. Appendix B reports the algorithms in a pseudo-code format. The ANOVA output that motivated why particular interaction effects draw attention is found in Appendix C. Appendix D serves as an addendum for the discussion in Section 7.1.

## 1.4 Contribution of the dissertation

While this study models the expected bidding behavior of contractors, the new insights that are generated have mainly an impact on the governmental policies. Since project and bidding data are scarce and since the societal value of the projects inhibit an empirical assessment of tender policies, the public sector could rely on the development of theoretical models to steer decision making.

The subsequent chapters prove the added value of incentive creation mechanisms in order to maintain an appropriate level of competitiveness in the long run. Without governmental policies, the social benefits suffer from inviting more than two bidders for a high-risk PPP together with the danger of the winner's curse. The dissertation especially underlines the efficacy of governmental policies in heterogeneous markets (i.e., markets in which contractors may have a competitive advantage on their opponents). While these tendencies were already acknowledged by most policy makers, the views on the expected benefits differ across different jurisdictions, but the PPP model of this research project offers arguments for a general convergence of opinions. First of all, the standardization of contracts and processes could reduce the project-specific investment burden and would inflate investment incentives earlier in the project sequence. A second new insight relates to the impact of the fractional reimbursement of the losers’ pre-tender research cost. Especially in high-risk settings with more than two heterogeneous players, the reimbursements lead to more price competition and increased investment incentives. Besides, having a cemented pipeline amplifies the competitive forces which thus offsets the additional governmental cost of the reimbursements.

Evidently, the insights from this dissertation are not only related to practitioners, but also contribute to the academic literature on procurement auctions and PPP bidding in particular. Incurring heterogeneity in the bidder’s experience levels revealed new insights on the asymmetric nature of the equilibria. Moreover, this dissertation pioneers in building a setting that entails a magnitude of characteristics that have been studied in distinct research streams: uncertainty in the project outcome, the investment decision to create a cost and knowledge advantage, the impact of incentive creation mechanisms and the consideration of a sequential project format. The remainder of this work proves that these determinants show important interactions that have not yet been considered in a generic setting. Also the PPP literature, that is currently mainly driven by empirical research on past project experiences, benefits from the predictive and theoretical insights. While the majority of academic PPP papers look at one-to-one contractual arrangements between the government and the contractor, this study introduces the competitive aspect of decision making under uncertainty.

# Chapter 2 Literature review on project management in PPPs

The purpose of this chapter is twofold. Firstly, it aims to clarify the PPP glossary and the different aspects of the PPP procurement process. Secondly, it aims to create a map of the contemporary research topics of interest on which this dissertation can be pinned, in order to stress the contribution of the research project, highlighting some aspects that have not yet been extensively emphasized in previous studies.

## 2.1 Delineation of the literature study

PPP projects have been studied in a multiplicity of disciplines, like legal sciences, political sciences and economics. Within the operations management field though, coverage has been limited. Nonetheless, the project management literature and construction literature has dealt with important aspects of the PPP management process. Therefore, in order to set the research context, we opted to follow the methodologies of the literature reviews of Al-Sharif and Kaka (2004), Ke et al. (2009) and Tang et al. (2010). As a result, this review covers the literature of six important construction journals between 2006 and 2014. In addition, the key and often referenced articles concerning PPPs and bidding in a public procurement setting have been included in the discussion.

The selection of the six journals is based on the journal ranking list of Chau (1997): Journal of Construction Engineering and Management (JCEM), International Journal of Project Management (IJPM), Construction Management and Economics (CME), Engineering, Construction and Architectural Management (ECAM), Journal of Management in Engineering (JME). Within the top six, also Proceedings of Institution of Civil Engineers – Civil Engineering (PICE-CE) is ranked. This journal has not been considered due to the negligible number of PPP-related papers and instead, Public Money & Management (PMM) is added to the reference list. While it is rather a drawback that there are no more recent rankings of construction journals, an investigation of the top articles by search engines confirms that the six selected journals are appropriate and representative for the PPP literature. A keyword search on "PPP", "PFI", "Public-Private", "Privately financed", "BOT" and "DBFM" led to the database of selected references. A content analysis is necessary to confirm whether the main theme of the paper is related to PPPs.

Next to some methodological classifications, this chapter also classifies the literature in line with the PPP research landscape that was drawn by Yuan et al. (2009). In the classification schemes, only the selected papers that were published between 2006 and 2014 in one of the six aforementioned journals are categorized. In total, 205 papers were selected for the PPP literature classification schemes. A classification is always suffering from some subjectivity, but the purpose is to classify the papers according to their focal purpose. Furthermore, the categories are non-exclusive, so that a paper may appear in several categories.

## 2.2 Classification of the PPP literature

### 2.2.1 Country of application

Every country has its own experience with PPP projects and it is argued that every country should be approached differently (e.g., Chan et al. 2009, McQuaid and Scherrer 2010, Zwikael and Ahn 2011, Rebeiz 2012). The drivers to engage in PPPs may differ and each jurisdiction is subject to its own risk factors. Developing countries deal with different challenges concerning for instance the external conditions, like political stability, corruption eradication or financial transparency (Wibowo and Alfen 2014). Therefore, a large number of empirical studies refrain from extrapolating the findings to a global perspective, but stick to a country-specific study (Figure 2.1). Nevertheless, also other countries welcome PPP projects, but have not yet been studied in an academic vein.

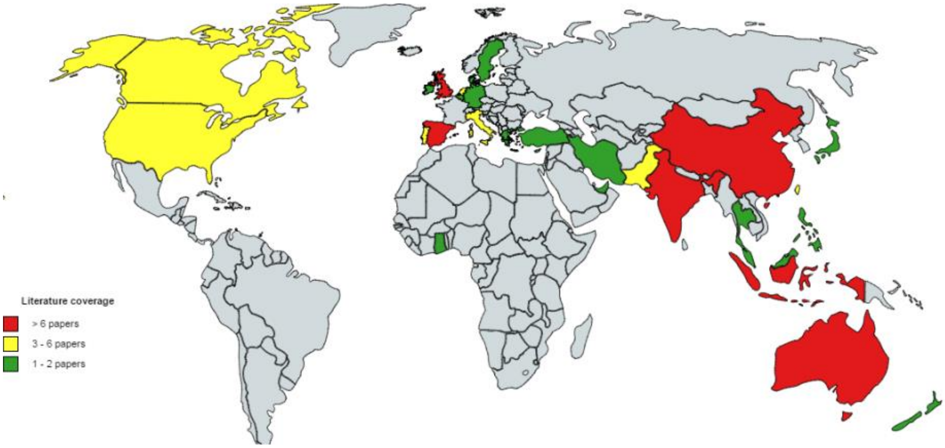


Figure 2.1 Geographical representation of PPP applications in investigated papers

### 2.2.2 Sector of application

Next to the geographic extension of the academic PPP research, also the sector focus has been widened (Table 2.1). While the majority of papers does not limits its scope to a particular sector, others concentrate on a specific industry for their empirical investigation or their theoretic application. The economic infrastructure, usually dealing with the transportation sector, is still receiving the largest interest. Nevertheless, since social PPPs become more important in both developing as well as developed countries, one could expect this could be also reflected in the academic literature.

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|---|---|
| Transportation | Abednego & Ogunlana (2006), Acerete et al. (2009), Ahmadjian & Collura (2012), Algarni et al. (2007), Anastasopoulos et al. (2014), Ashuri et al. (2012), Aziz (2007a,b), Baeza & Vassallo (2010), Brandao & Saraiva (2008), Carbonara et al. (2014b), Carpintero & Petersen (2014), Chang (2013[b]), Cheah & Liu (2006), Chiara & Garvin (2008), da Cruz & Marques (2014), Garvin (2010), Girmscheid (2009), Henjewele et al. (2011, 2014), Huang & Chou (2006), Iyer & Sagheer (2010, 2011), Jupe (2007), Kokkaew & Chiara (2010), Kraft & Molenaar (2014), Laishram & Kalidindi (2009), Lenferink et al. (2013), Medda (2007), Meduri & Annamalai (2013), Ng et al. (2007[a]), Papajohn et al. (2011), Park & Chang (2013), Rajan et al. (2014), Rangel & Galende (2010), Rose & Manley (2012), Shan et al. (2010), Shaoul (2006), Shaoul et al. (2011), Singh & Kalidindi (2006), Soliño & Vassallo (2009), Subprasom & Chen (2006), Tamayo et al. (2014), Tawiah & Russell (2008), Thomas et al. (2006), Vassallo et al. (2012), Walker & Jacobsson (2014), Wibowo et al. (2012), Xiong & Zhang (2014), Xu & Moon (2014), Xu et al. (2012), Zhang (2009) |
| Healthcare | Acerete et al. (2012), Barretta et al. (2008), Cruz & Marques (2012, 2013b), Cuthbert & Cuthbert (2010), De Marco & Mangano (2013), De Marco et al. (2012), Hellowell & Pollock (2007), Henjewele et al. (2011), Holmes et al. (2006), Jefferies & McGeorge (2009), McMurray (2007), Nisar (2013), Shaoul et al. (2008), Vecchi et al. (2010) |
| Water provision | Boudet et al. (2011), Chen (2009), Choi et al. (2010), Hassanein & Khalifa (2007), Jang et al. (2014), Lee & Yu (2011), Marques & Berg (2011), Meng et al. (2011), Park et al. (2013), Wibowo & Mohamed (2010) |
| Education | da Cruz & Marques (2012), Demirag & Khadaroo (2010), Jefferies & McGeorge (2009), Liu & Wilkinson (2014[b]), Nisar (2013), Petersen (2010), Reeves & Ryan (2007), Van Gestel et al. (2014), Wang (2014) |
| Housing | Abdul-Aziz (2012), Norris & Coates (2010), Trangkanont & Charoenngam (2014), Wang et al. (2014), Yuan et al. (2012[a]) |
| Defense & security | Jefferies & McGeorge (2009), Massey & Shidlo (2010), Ortiz (2010) |
| Energy | Chowdhury & Charoenngam (2009), Rebeiz (2012), Sobhiyah et al. (2009) |
| Waste management | Kleiss & Imura (2006), Zheng & Tiong (2010) |

Table 2.1 Sector of interest in PPP papers

### 2.2.3 Stakeholder perspective

Yuan et al. (2009) define five stakeholder relationships in the PPP deal. These have received attention in varying degrees (Table 2.2). The public angle of the PPP involvement has been extensively studied. Topics include for instance the question whether it is interesting to execute a particular project as a PPP. Moreover, the drivers for the public sector have been investigated from an international perspective. Also the contracting mechanism needs to be carefully designed and one should be able to handle potential governance issues. Section 2.2.5.2 goes more into detail on these topics that aim to align the private sector objectives with the public and social needs.

Evidently, the second stakeholder concerns the private sector. However, there are significantly less studies that solely focus on the private side of the agreement. This might be a consequence of the fact that private empirical data are scarce and the SPVs are often reluctant to share information about their strategies. Nevertheless, the public-private relationship, which is also considered as a stakeholder relationship, is a well-studied perspective. This is due to the fact that PPPs involve specific public-private challenges like the risk allocation mechanism. Furthermore, financiers also have an important stake as a third party stakeholder. Finally, Yuan et al. (2009) appointed the subcontractors as a fifth important group of stakeholders. However, most research on infrastructure subcontracting will also be applicable in the PPP context. Moreover, the pre-formed SPVs that enter the PPP tender already integrate different subcontractors.

| | |
|---|---|
| Public sector | Abdul-Aziz (2012), Acerete et al. (2009), Acerete et al. (2012), Ahmadjian & Collura (2012), Algarni et al. (2007), Anastasopoulos et al. (2014), Aziz (2007[a,b]), Badu et al. (2013), Bailey et al. (2009), Boin & Smith (2006), Chan et al. (2009, 2010[a], 2010[b]), Charles et al. (2008), Cheung & Chan (2011), Cheung et al. (2010), Cruz & Marques (2014), da Cruz & Marques (2012, 2014), Daube et al. (2008), De Marco & Mangano (2013), De Marco & Mangano (2013), De Marco et al. (2012), Demirag & Khadaroo (2010), Doloi (2009), Garvin (2010), Girmscheid (2009), Hellowell & Pollock (2007), Henjewele et al. (2011), Jupe (2007), Kleiss & Imura (2006), Koch & Buser (2006), Kumaraswamy et al. (2007), Liu & Wilkinson (2014[a,b]), Mahalingam (2010), McMurray (2007), McQuaid & Scherrer (2010), Meduri & Annamalai (2013), Meng et al. (2011), Ng & Wong (2007), Norris & Coates (2010), Ortiz (2010), Papajohn et al. (2011), Petersen (2010), Pollock & Price (2008), Pollock et al. (2007), Raisbeck et al. (2010), Reeves & Ryan (2007), Shaoul (2006), Shaoul et al. (2008, 2011), Soliño & Vassallo (2009), Tamayo et al. (2014), Tang et al. (2013), Tang & Shen (2013), Tawiah & Russell (2008), Vecchi et al. (2010), Vives et al. (2010), Wang (2014), Weihe (2008), Weisheng et al. (2013), Wibowo & Kochendoerfer (2011), Xie & Ng (2013), Xiong & Zhang (2014), Yuan et al. (2012[a]) |
| Private sector | Arboleda & Abraham (2006), Chang (2013[c]), Chiang et al. (2010), Chiara & Garvin (2008), Doloi (2013), El-Diraby & Gill (2006), Gruneberg et al. (2007), Iyer & Sagheer (2012), Jones & Noble (2008), Kokkaew & Chiara (2010), McCowan & Mohamed (2007), Ng et al. (2010), Park & Chang (2013), Raisbeck & Tang (2013), Rebeiz (2012), Swaffield & McDonald (2008), Thomas et al. (2006), Wibowo & Alfen (2013), Xu et al. (2012), Zhang (2009) |
| Public-private | Abednego & Ogunlana (2006), Ashuri et al. (2012), Aziz (2007[b]), Baeza & Vassallo (2010), Barretta et al. (2008), Boudet et al. (2011), Brandao & Saraiva (2008), Carbonara et al. (2014[a,b]), Carpintero & Petersen (2014), Carrillo et al. (2006, 2008), Chan et al. (2011), Chang (2013[a,b]), Cheah & Liu (2006), Chen (2009), Chen & Doloi (2008), Choi et al. (2010), Chowdhury et al. (2011), Clifton & Duffield (2006), Cruz & Marques (2013[a]), Cruz & Marques (2013[b]), Cuthbert & Cuthbert (2010), De Schepper et al. (2014), Devapriya (2006), Dulaimi et al. (2010), El-Gohary et al. (2006), Fischer et al. (2006), Gurgun & Touran (2014), Hanaoka & Palapus (2012), Hassanein & Khalifa (2007), Henisz (2006), Henjewele et al. (2014), Ho (2006), Ho & Hsu (2014), Holmes et al. (2006), Huang & Chou (2006), Huang & Pi (2009, 2014), Hwang et al. (2012), Iyer & Sagheer (2010, 2011), Javed et al. (2014), Jefferies (2006), Jefferies & McGeorge (2009), Jin (2010, 2011), Jin & Doloi (2008), Jin & Zhang (2011), Ke et al. (2009), Ke et al. (2010), Ke et al. (2011), Khazaeni et al. (2012), Kong et al. (2008), Kraft & Molenaar (2014), Lee & Yu (2011), Lee & Schaufelberger (2014), Leiringer (2006), Lenferink et al. (2013), Li & Zou (2011), Liou & Huang (2008), Liou et al. (2011), Liu & Cheah (2009), Liu et al. (2014), Ng & Loosemore (2007), Marques & Berg (2011), Massey & Shidlo (2010), Medda (2007), Ng & Wong (2006), Ng et al. (2007[a]), Nisar (2013), Park et al. (2013), Raisbeck (2008), Rajan et al. (2014), Rangel & Galende (2010), Regan et al. (2011), Robinson & Scott (2009), Rose & Manley (2012), Roumboutsos & Anagnostopoulos (2008), Roumboutsos & Saussier (2014), Ruuska & Teigland (2009), Salman et al. (2007), Shan et al. (2010), Shen et al. (2007), Shen et al. (2006), Singh & Kalidindi (2006), Smyth (2008), Smyth & Edkins (2007), Sobhiyah et al. (2009), Subprasom & Chen (2006), Tang et al. (2010), Trangkanont & Charoenngam (2014), Tserng et al. (2012), Van Gestel et al. (2014), van Gestel et al. (2008), van Marrewijk et al. (2008), Vassallo et al. (2012), Walker & Jacobsson (2014), Wang et al. (2014), Wibowo (2006), Wibowo & Alfen (2014), Wibowo & Mohamed (2010), Wibowo et al. (2012), Xu & Moon (2014), Xu et al. (2010), Yang et al. (2010), Ye & Liu (2008), Yuan et al. (2009), Yuan et al. (2010), Yuan et al. (2012[b]), Zhang (2006[a,b]), Zheng & Tiong (2010), Zou et al. (2014) |
| Third party | Chiang & Cheng (2009), Laishram & Kalidindi (2009), Liou et al. (2011), Park & Chang (2013) |

Table 2.2 Stakeholder perspective of the investigated papers

### 2.2.4 Type of the research

Before heading to the topic-specific classification, the contemporary PPP research from the selected construction journals may be classified with respect to the type of study (Table 2.3 and Table 2.4). Empirical PPP papers study the as-is status of the market or guide towards a to-be situation based on a consultation of industry experts. Since more PPP projects reach financial close or are even already nearly at the end of their concession period, the ex post evaluation literature is proliferating. Especially the number of county- or sector-specific case studies, classified under qualitative empirical research, is on the rise.

The quantitative empirical research is not case-specific but typically collects data through surveys and interviews or from secondary data sources. The breakdown of the data sources in Table 2.5 emphasizes the important reliance on expert data. Recently, more and more studies gather secondary data sources, but this fraction is still significantly lower than for the subjective data sources. This is caused by a lack of quantitative and consistent project data. That is a drawback for many studies, especially because a low response rate and a lack of detailed knowledge are often encountered problems, disturbing the validity of the survey findings. The discussion of the mostly common methodologies that process these data is postponed to the subject-specific discussion of Section 2.2.5.

While PMM is merely an outlet for case studies, the other journals accommodate both qualitative as well as quantitative papers. JCEM, CME and, to a smaller extent, IJPM also invite theoretical papers. The papers that carry the theoretical heading are very diverse though, ranging from studies that propose theoretical or conceptual frameworks to analytical and experimental studies of PPP determinants like risk allocation mechanisms, pricing attributes or bidding models.

| | |
|---|---|
| Empirical – quantitative | Acerete et al. (2009), Algarni et al. (2007), Anastasopoulos et al. (2014), Badu et al. (2013), Boudet et al. (2011), Carrillo et al. (2008), Chan et al. (2009, 2010[a,b]), Chan et al. (2011), Chen & Doloi (2008), Cheung & Chan (2011), Cheung et al. (2010), Chiang & Cheng (2009), Choi et al. (2010), Cruz & Marques (2013[a]), De Marco & Mangano (2013), De Marco et al. (2012), Demirag & Khadaroo (2010), Doloi (2009, 2013), Hassanein & Khalifa (2007), Hellowell & Pollock (2007), Henjewele et al. (2011, 2014), Hwang et al. (2012), Javed et al. (2014), Jin (2010, 2011), Jin & Doloi (2008), Jin & Zhang (2011), Ke et al. (2010), Ke et al. (2011), Meduri & Annamalai (2013), Ng & Wong (2006, 2007), Raisbeck (2008), Raisbeck et al. (2010), Raisbeck & Tang (2013), Rajan et al. (2014), Rangel & Galende (2010), Roumboutsos & Anagnostopoulos (2008), Salman et al. (2007), Smyth (2008), Smyth & Edkins (2007), Swaffield & McDonald (2008), Tang et al. (2013), Tang & Shen (2013), Vecchi et al. (2010), Wang (2014), Wibowo & Alfen (2014), Wibowo & Mohamed (2010), Xu et al. (2010), Yang et al. (2010), Yuan et al. (2009), Yuan et al. (2012[a]), Yuan et al. (2010), Yuan et al. (2012[b]), Zhang (2006[a,b]), Zou et al. (2014) |
| Empirical - qualitative | Abdul-Aziz (2012), Abednego & Ogunlana (2006), Acerete et al. (2012), Aziz (2007[a,b]), Baeza & Vassallo (2010), Bailey et al. (2009), Barretta et al. (2008), Boin & Smith (2006), Carpintero & Petersen (2014), Carrillo et al. (2006), Charles et al. (2008), Chen (2009), Chowdhury & Charoenngam (2009), Chowdhury et al. (2011), Clifton & Duffield (2006), Cruz & Marques (2013[b]), Cuthbert & Cuthbert (2010), da Cruz & Marques (2012, 2014), Daube et al. (2008), De Schepper et al. (2014), Devapriya (2006), Dulaimi et al. (2010), El-Diraby & Gill (2006), Fischer et al. (2006), Garvin (2010), Gruneberg et al. (2007), Gurgun & Touran (2014), Henjewele et al. (2014), Holmes et al. (2006), Jang et al. (2014), Jefferies (2006), Jefferies & McGeorge (2009), Jones & Noble (2008), Jupe (2007), Kleiss & Imura (2006), Koch & Buser (2006), Kraft & Molenaar (2014), Lee & Yu (2011), Lee & Schaufelberger (2014), Leiringer (2006), Lenferink et al. (2013), Liu & Wilkinson (2014[a,b]), Mahalingam (2010), Marques & Berg (2011), Massey & Shidlo (2010), McMurray (2007), McQuaid & Scherrer (2010), Meng et al. (2011), Nisar (2013), Norris & Coates (2010), Ortiz (2010), Papajohn et al. (2011), Park & Chang (2013), Petersen (2010), Pollock & Price (2008), Pollock et al. (2007), Rebeiz (2012), Reeves & Ryan (2007), Regan et al. (2011), Robinson & Scott (2009), Rose & Manley (2012), Ruuska & Teigland (2009), Shaoul (2006), Shaoul et al. (2008, 2011), Shen et al. (2006), Singh & Kalidindi (2006), Sobhiyah et al. (2009), Soliño & Vassallo (2009), Trangkanont & Charoenngam (2014), Tserng et al. (2012), Van Gestel et al. (2014), van Gestel et al. (2008), van Marrewijk et al. (2008), Vassallo et al. (2012), Walker & Jacobsson (2014), Wang et al. (2014), Weihe (2008), Weisheng et al. (2013), Ye & Liu (2008), Zheng & Tiong (2010) |

Table 2.3 Type of research in the investigated papers

| | |
|---|---|
| Theoretical | Ahmadjian & Collura (2012), Arboleda & Abraham (2006), Ashuri et al. (2012), Brandao & Saraiva (2008), Carbonara et al. (2014[a,b]), Chang (2013[b,c]), Cheah & Liu (2006), Chiang et al. (2010), Chiara & Garvin (2008), Cruz & Marques (2012, 2014), El-Gohary et al. (2006), Girmscheid (2009), Hanaoka & Palapus (2012), Ho (2006), Ho & Hsu (2014), Huang & Chou (2006), Huang & Pi (2009, 2014), Iyer & Sagheer (2010, 2011), Javed et al. (2014), Khazaeni et al. (2012), Kokkaew & Chiara (2010), Kong et al. (2008), Kumaraswamy et al. (2007), Li & Zou (2011), Liou & Huang (2008), Liou et al. (2011), Liu & Cheah (2009), Liu et al. (2014), Ng & Loosemore (2007), McCowan & Mohamed (2007), Medda (2007), Ng et al. (2007[a]), Ng et al. (2010), Park et al. (2013), Roumboutsos & Saussier (2014), Shan et al. (2010), Shen et al. (2007), Subprasom & Chen (2006), Tawiah & Russell (2008), Thomas et al. (2006), Tserng et al. (2012), Vives et al. (2010), Wibowo (2006), Wibowo & Alfen (2013), Wibowo & Kochendoerfer (2011), Wibowo et al. (2012), Xie & Ng (2013), Xiong & Zhang (2014), Xu & Moon (2014), Xu et al. (2012), Zhang (2009) |

Table 2.4 Type of research in the investigated papers (ctd.)

| | |
|---|---|
| Secondary data | Acerete et al. (2009), Acerete et al. (2012), Anastasopoulos et al. (2014), Aziz (2007[a]), Baeza & Vassallo (2010), Cruz & Marques (2013[a]), Cuthbert & Cuthbert (2010), Daube et al. (2008), De Marco & Mangano (2013), De Marco et al. (2012), De Schepper et al. (2014), Hassanein & Khalifa (2007), Hellowell & Pollock (2007), Henjewele et al. (2014), Jefferies & McGeorge (2009), Jones & Noble (2008), Kraft & Molenaar (2014), Leiringer (2006), Lenferink et al. (2013), Mahalingam (2010), Meduri & Annamalai (2013), Norris & Coates (2010), Park & Chang (2013), Pollock & Price (2008), Pollock et al. (2007), Raisbeck et al. (2010), Rajan et al. (2014), Reeves & Ryan (2007), Shaoul (2006), Shaoul et al. (2008), van Gestel et al. (2008), Vassallo et al. (2012), Vecchi et al. (2010), Weisheng et al. (2013), Zheng & Tiong (2010) |
| Interview | Abdul-Aziz (2012), Abednego & Ogunlana (2006), Badu et al. (2013), Barretta et al. (2008), Carrillo et al. (2006), Charles et al. (2008), Dulaimi et al. (2010), El-Diraby & Gill (2006), Gruneberg et al. (2007), Holmes et al. (2006), Jefferies & McGeorge (2009), Jin (2011), Jones & Noble (2008), Leiringer (2006), Lenferink et al. (2013), Liu & Wilkinson (2014[a,b]), Mahalingam (2010), Ng & Wong (2006), Norris & Coates (2010), Reeves & Ryan (2007), Robinson & Scott (2009), Rose & Manley (2012), Ruuska & Teigland (2009), Sobhiyah et al. (2009), Swaffield & McDonald (2008), Tang & Shen (2013), van Gestel et al. (2008), Weisheng et al. (2013), Xu et al. (2010), Zhang (2006[b]) |
| Survey | Abdul-Aziz (2012), Algarni et al. (2007), Badu et al. (2013), Carrillo et al. (2006, 2008), Chan et al. (2009, 2010[a,b]), Chan et al. (2011), Chen & Doloi (2008), Cheung & Chan (2011), Cheung et al. (2010), Chiang & Cheng (2009), Clifton & Duffield (2006), Demirag & Khadaroo (2010), Doloi (2009), Henjewele et al. (2014), Hwang et al. (2012), Jin (2010, 2011), Jin & Doloi (2008), Jin & Zhang (2011), Ke et al. (2010), Ke et al. (2011), Khazaeni et al. (2012), Kraft & Molenaar (2014), Kumaraswamy et al. (2007), Ng & Wong (2006), Papajohn et al. (2011), Raisbeck (2008), Raisbeck & Tang (2013), Rangel & Galende (2010), Roumboutsos & Anagnostopoulos (2008), Salman et al. (2007), Smyth (2008), Smyth & Edkins (2007), Swaffield & McDonald (2008), Tang & Shen (2013), Wibowo & Alfen (2014), Wibowo & Mohamed (2010), Xu et al. (2010), Yang et al. (2010), Yuan et al. (2009), Yuan et al. (2012[a]), Yuan et al. (2010), Yuan et al. (2012[b]), Zhang (2006[a,b]), Zou et al. (2014) |

Table 2.5 Data sources of the investigated papers

### 2.2.5 Subject of study: A process classification

The PPP contracting format is complex. The longevity and complexity cause major extra risks and the need for planning is invaluable (Grimsey and Lewis 2002, Ng and Loosemore 2007, Zwikael and Sadeh 2007). This planning appears in multiple stages of the PPP contract and the sequel of this section offers an overview of the state-of-the-art from a process perspective. The framework of Yuan et al. (2009) is slightly simplified in order to easily decompose the investigated papers and allocate them to the appropriate heading.

The proposed classification scheme follows the essential steps of the PPP decision process (Table 2.6). Once an initial project concept is launched at the public side, the government needs to decide, often assisted by advisory institutions, on the appropriate procurement method. The PPP/Non-PPP literature studies these driving and inhibiting factors that influence the PPP decision. Once the PPP tender document is launched, we assume the procurement stage has started (Table 2.7). The public and private stakeholders have different challenges to face. The tendering governmental institution develops an appropriate contract mechanism. Moreover, the public entity decides on the prequalification parameters in order to determine which consortia move to the final bidding stages and on the decision mechanism to select the preferred bidder. The private sector consortia need to assess the feasibility of the project and invest in pre-tender research to improve the accuracy and the quality of the bid proposal. Contractor bidding refers to setting an appropriate price for the project. The risk identification and assessment and the risk allocation steps have both public as well as private repercussions. Once the preferred bidder is selected, the governance literature aids in managing and controlling the contract. Last but not least, an important stretch of research draws conclusions from ex post investigations of past projects resulting in essential key performance indicators. The major research questions for each category, together with the prominent methodologies that are specific for the PPP research context, are discussed in the subsequent sections.

| | |
|---|---|
| PPP/Non-PPP | Acerete et al. (2009), Acerete et al. (2012), Algarni et al. (2007), Badu et al. (2013), Bailey et al. (2009), Chan et al. (2009), Cheung & Chan (2011), Cruz & Marques (2014), da Cruz & Marques (2014), Girmscheid (2009), Henjewele et al. (2011), Laishram & Kalidindi (2009), Lenferink et al. (2013), McQuaid & Scherrer (2010), Rose & Manley (2012), Salman et al. (2007), Vives et al. (2010), Weisheng et al. (2013), Xie & Ng (2013), Yuan et al. (2012[a]) |
| Procurement | Table 2.7 |
| Governance | Abdul-Aziz (2012), Barretta et al. (2008), Boudet et al. (2011), Chang (2013[b,c]), Charles et al. (2008), Chowdhury et al. (2011), Cruz & Marques (2013[b]), da Cruz & Marques (2012, 2014), De Schepper et al. (2014), Devapriya (2006), El-Diraby & Gill (2006), El-Gohary et al. (2006), Fischer et al. (2006), Henisz (2006), Javed et al. (2014), Jones & Noble (2008), Koch & Buser (2006), Kraft & Molenaar (2014), Ng & Wong (2007), Nisar (2013), Robinson & Scott (2009), Smyth (2008), Smyth & Edkins (2007), Tang et al. (2013), Tserng et al. (2012), Van Gestel et al. (2014), van Gestel et al. (2008), van Marrewijk et al. (2008), Walker & Jacobsson (2014), Wang et al. (2014), Ye & Liu (2008), Yuan et al. (2009), Yuan et al. (2010), Zou et al. (2014) |
| Ex post evaluation | Ahmadjian & Collura (2012), Anastasopoulos et al. (2014), Carpintero & Petersen (2014), Chen (2009), Chen & Doloi (2008), Chowdhury & Charoenngam (2009), Cuthbert & Cuthbert (2010), da Cruz & Marques (2012), Demirag & Khadaroo (2010), Dulaimi et al. (2010), Gurgun & Touran (2014), Hassanein & Khalifa (2007), Hellowell & Pollock (2007), Henjewele et al. (2014), Holmes et al. (2006), Hwang et al. (2012), Jang et al. (2014), Jefferies (2006), Jefferies & McGeorge (2009), Jupe (2007), Kleiss & Imura (2006), Koch & Buser (2006), Lee & Yu (2011), Leiringer (2006), Liu & Wilkinson (2014[a,b]), Mahalingam (2010), Massey & Shidlo (2010), McMurray (2007), Meduri & Annamalai (2013), Ng & Wong (2006), Norris & Coates (2010), Ortiz (2010), Papajohn et al. (2011), Park & Chang (2013), Petersen (2010), Pollock & Price (2008), Pollock et al. (2007), Raisbeck et al. (2010), Rajan et al. (2014), Reeves & Ryan (2007), Rose & Manley (2012), Shaoul (2006), Shaoul et al. (2008, 2011), Trangkanont & Charoenngam (2014), van Marrewijk et al. (2008), Vecchi et al. (2010), Walker & Jacobsson (2014), Wang (2014), Wang et al. (2014), Weihe (2008), Yang et al. (2010), Zheng & Tiong (2010) |
| Key success factors | Aziz (2007[b]), Carrillo et al. (2006), Chan et al. (2009, 2010[a,b]), Chowdhury & Charoenngam (2009), Doloi (2013), Dulaimi et al. (2010), Garvin (2010), Gurgun & Touran (2014), Hwang et al. (2012), Jefferies (2006), Meng et al. (2011), Ruuska & Teigland (2009), Tang et al. (2013), Wibowo & Alfen (2014), Yuan et al. (2009), Yuan et al. (2012[a]), Yuan et al. (2010), Yuan et al. (2012[b]) |

Table 2.6 Subject of study of the investigated papers

| | |
|---|---|
| Mechanism & contracting | Abdul-Aziz (2012), Aziz (2007[a]), Carrillo et al. (2008), Cruz & Marques (2012), Cruz & Marques (2013[a]), Daube et al. (2008), De Marco & Mangano (2013), De Marco et al. (2012), Garvin (2010), Ho (2006), Ho & Hsu (2014), Javed et al. (2014), Roumboutsos & Saussier (2014), Soliño & Vassallo (2009), Subprasom & Chen (2006), Tamayo et al. (2014), Tang et al. (2013), Tang & Shen (2013), Xiong & Zhang (2014) |
| Prequalification | Doloi (2009), Kumaraswamy et al. (2007) |
| Preferred bidder | Baeza & Vassallo (2010), Zhang (2006[a,b]) |
| Pre-tender research | Carrillo et al. (2008), Chiara & Garvin (2008), Ho (2006), Ho & Hsu (2014), Jefferies & McGeorge (2009), McCowan & Mohamed (2007), Raisbeck & Tang (2013), Rangel & Galende (2010), Roumboutsos & Saussier (2014), Zhang (2006[a,b]) |
| Contractor bidding | Arboleda & Abraham (2006), Ashuri et al. (2012), Baeza & Vassallo (2010), Carbonara et al. (2014[a]), Cheah & Liu (2006), Chiang et al. (2010), Cruz & Marques (2013[a]), Hanaoka & Palapus (2012), Ho (2006), Ho & Hsu (2014), Huang & Chou (2006), Huang & Pi (2009, 2014), Iyer & Sagheer (2011, 2012), Liou & Huang (2008), Liou et al. (2011), Liu & Cheah (2009), Liu et al. (2014), Ng et al. (2007[a]), Ng et al. (2010), Park et al. (2013), Shan et al. (2010), Shen et al. (2007), Subprasom & Chen (2006), Swaffield & McDonald (2008), Wibowo (2006), Wibowo & Alfen (2013), Wibowo et al. (2012), Xu & Moon (2014), Xu et al. (2012), Zhang (2009) |
| Risk identification & assessment | Ashuri et al. (2012), Boin & Smith (2006), Brandao & Saraiva (2008), Carbonara et al. (2014[b]), Chan et al. (2011), Chang (2013[b,c]), Cheah & Liu (2006), Chiara & Garvin (2008), Choi et al. (2010), Cruz & Marques (2012), Gruneberg et al. (2007), Huang & Chou (2006), Huang & Pi (2009, 2014), Hwang et al. (2012), Iyer & Sagheer (2010, 2011), Ke et al. (2011), Kokkaew & Chiara (2010), Kong et al. (2008), Lee & Schaufelberger (2014), Li & Zou (2011), Liou & Huang (2008), Liu & Cheah (2009), Liu et al. (2014), Marques & Berg (2011), Park et al. (2013), Raisbeck (2008), Rebeiz (2012), Regan et al. (2011), Roumboutsos & Anagnostopoulos (2008), Shan et al. (2010), Thomas et al. (2006), Vassallo et al. (2012), Wibowo (2006), Wibowo & Alfen (2013), Wibowo & Kochendoerfer (2011), Wibowo & Mohamed (2010), Xiong & Zhang (2014), Xu & Moon (2014) |
| Risk allocation | Abednego & Ogunlana (2006), Ashuri et al. (2012), Brandao & Saraiva (2008), Carbonara et al. (2014[a]), Carbonara et al. (2014[b]), Chan et al. (2011), Chang (2013[b,c]), Cheah & Liu (2006), Gruneberg et al. (2007), Huang & Chou (2006), Huang & Pi (2009, 2014), Hwang et al. (2012), Iyer & Sagheer (2011), Javed et al. (2014), Jin (2010, 2011), Jin & Doloi (2008), Jin & Zhang (2011), Ke et al. (2010), Khazaeni et al. (2012), Lee & Yu (2011), Liu & Cheah (2009), Liu et al. (2014), Ng & Loosemore (2007), Marques & Berg (2011), Medda (2007), Park et al. (2013), Raisbeck (2008), Roumboutsos & Anagnostopoulos (2008), Shan et al. (2010), Shen et al. (2006), Singh & Kalidindi (2006), Sobhiyah et al. (2009), Vassallo et al. (2012), Wibowo (2006), Wibowo & Kochendoerfer (2011), Wibowo & Mohamed (2010), Wibowo et al. (2012), Xu & Moon (2014), Xu et al. (2010) |

Table 2.7 Subject of study of investigated papers: procurement-related topics

| | |
|---|---|
| Financial analysis | Acerete et al. (2009), Ahmadjian & Collura (2012), Brandao & Saraiva (2008), Carbonara et al. (2014[a]), Cheah & Liu (2006), Chiang et al. (2010), Cruz & Marques (2012), Girmscheid (2009), Hanaoka & Palapus (2012), Hassanein & Khalifa (2007), Huang & Chou (2006), Huang & Pi (2009, 2014), Iyer & Sagheer (2012), Kong et al. (2008), Liou & Huang (2008), Liu & Cheah (2009), McCowan & Mohamed (2007), Ng et al. (2007), Ng et al. (2010), Park & Chang (2013), Shen et al. (2007), Vecchi et al. (2010), Wibowo (2006), Wibowo & Alfen (2013), Wibowo & Kochendoerfer (2011), Wibowo et al. (2012), Xiong & Zhang (2014), Zhang (2009) |
| Real options | Arboleda & Abraham (2006), Ahuri et al. (2012), Brandao & Saraiva (2008), Carbonara et al. (2014[b]), Cheah & Liu (2006), Cruz & Marques (2012), Huang & Chou (2006), Huang & Pi (2009, 2014), Iyer & Sagheer (2011), Liu & Cheah (2009), Liu et al. (2014), Park et al. (2013), Shan et al. (2010) |
| Economic theories | Chang (2013[a]), Jin (2010, 2011), Jin & Doloi (2008), Jin & Zhang (2011), Roumboutsos & Saussier (2014), Tserng et al. (2012) |
| Game theory | Chang (2013[b]), Hanaoka & Palapus (2012), Ho (2006, 2014), Javed et al. (2014), Medda (2007), Shen et al. (2007), Tserng et al. (2012) |
| Statistical hypotheses testing | Anastasopoulos et al. (2014), Chan et al. (2009, 2010[b]), Chan et al. (2011), Cheung & Chan (2011), Cheung et al. (2010), Chiang & Cheng (2009), Choi et al. (2010), Doloi (2013), Henjewele et al. (2011), Hwang et al. (2012), Ke et al. (2010), Ke et al. (2011), Meduri & Annamalai (2013), Ng & Wong (2006, 2007), Raisbeck (2008), Rajan et al. (2014), Roumboutsos & Anagnostopoulos (2008), Swaffield & McDonald (2008), Tang et al. (2013), Tang & Shen (2013), Wang (2014), Wibowo & Mohamed (2010), Yang et al. (2010), Yuan et al. (2009), Yuan et al. (2012[b]), Zhang (2006[a,b]) |
| Regression | Anastasopoulos et al. (2014), Cruz & Marques (2013[a]), De Marco & Mangano (2013), De Marco et al. (2012), Doloi (2009, 2013), Jin (2010), Jin & Doloi (2008), Liou & Huang (2008), Meduri & Annamalai (2013), Rajan et al. (2014), Rangel & Galende (2010) |
| Factor analysis | Badu et al. (2013), Chan (2010[a]), Doloi (2009, 2013), Rangel & Galende (2010), Tang & Shen (2013), Yuan et al. (2012[b]), Zhang (2006[a]) |
| Analytical hierarchy process | Khazaeni et al. (2012), Li & Zou (2011), Raisbeck & Tang (2013), Salman et al. (2007), Yuan et al. (2012[a]) |
| Fuzzy techniques | Jin (2011), Khazaeni et al. (2012), Laishram & Kalidindi (2009), Li & Zou (2011), Thomas et al. (2006), Xu et al. (2010), Yuan et al. (2010) |
| Probability models | Girmscheid (2009), Kong et al. (2008), Thomas et al. (2006), Wibowo (2006), Xie & Ng (2013), Xu & Moon (2014) |
| Binomial models | Arboleda & Abraham (2006), Ahuri et al. (2012), Iyer & Sagheer (2011), Wibowo et al. (2012) |
| Networks and structural models | Chowdhury et al. (2011), Iyer & Sagheer (2010), Jin (2011), Jin & Zhang (2011), Xu et al. (2012) |
| Simulation models | Arboleda & Abraham (2006), Ahuri et al. (2012), Brandao & Saraiva (2008), Carbonara et al. (2014[a]), Carbonara et al. (2014[b]), Cheah & Liu (2006), Cruz & Marques (2012), Girmscheid (2009), Hanaoka & Palapus (2012), Iyer & Sagheer (2011), Kokkaew & Chiara (2010), Liou & Huang (2008), Liou et al. (2011), Liu & Cheah (2009), Ng et al. (2007), Ng et al. (2010), Park et al. (2013), Shan et al. (2010), Wibowo & Alfen (2013), Wibowo et al. (2012), Xu & Moon (2014), Zhang (2009) |
| Programming and algorithms | Iyer & Sagheer (2012), Liou et al. (2011), Subprasom & Chen (2006), Wibowo & Kochendoerfer (2011) |

Table 2.8 Most important established and emerging methodologies in PPP research

#### *2.2.5.1 PPP or non-PPP?*

Why are governments engaging in PPP projects? The main drivers are country-dependent, but there is agreement about two general classes of motives: financially driven or macroeconomic drivers and efficiency driven or microeconomic drivers (Kumaraswamy et al. 2007, Chan et al. 2009, McQuaid and Scherrer 2010). The value for money paradigm is the variable that determines the attractiveness of a PPP project in comparison to a public sector comparator (Grimsey and Lewis 2002).

The papers that are classified under this PPP/non-PPP heading discuss methods and frameworks that trade-off the PPP option and an alternative investment procedure (e.g., Girmscheid 2009, Cheung and Chan 2011). The methodologies range from weighted assessments of positive and negative factors (Cheung & Chan 2011) to an economic net present value analysis that accounts for economic welfare (Girmscheid 2009). This category also entails survey-based and ex-post studies that discuss the skepticism for PPP agreements on the public side (e.g., Algarni et al. 2007, Henjewele et al. 2011). Consequently, the field is diverse and both positive as well as negative opinions color the research arena. But in general, one agrees that the possible success of the PPP as a contracting mechanism needs to be seen within a country-, a sector- and a project-specific context.

#### *2.2.5.2 Procurement mechanism and contracting*

The procuring entity needs to be well aware of the implications that result from the tendering documents. Evenhuis and Vickerman (2010) recommend the government to set up an appropriate tendering procedure so that the integration of tasks, the allocation of risks and adequate incentives achieve a balance between the interest of both parties. In our opinion, it is the ultimate goal of the contracting mechanism to select the most suitable and best-prepared contractor. Therefore, governments ought to take efforts to demolish barriers to entry (Carrillo et al. 2008). Government guarantees, discussed in Section 2.2.5.5, are also worth mentioning in this respect. From this stage onwards, the public sector also needs to be aware about the aftermaths of the contract, since asymmetric information and opportunistic bidding may cover perverse incentives of the consortia (Ho and Liu 2004, Evenhuis and Vickerman 2010). Hence, at the contracting and briefing stage, not only the stakeholders' roles and responsibilities but also the governance mechanisms need to be clearly defined.

A first topic that deserves attention in this respect is the determination of the appropriate payment mechanism (Aziz 2007[a]). A second aspect concerns the regulation versus the flexibility dimension. Subprasom and Chen (2006) discuss the impact of capacity regulation in toll road PPP contracts. These government-led requirements cap the flexibility for the contractor. Cruz and Marques (2012) claim that flexibility in contracts is necessary to cope with risk. Nevertheless, contractors might interpret this as an open door for renegotiations when particular risks or costs are overseen. Therefore, the output specifications, together with the renegotiation range and mechanism should be rigidly defined upfront (Javed et al. 2014, Xion and Zhang 2014).

A final aspect of the mechanism design, and that is a focal point of study in this dissertation, relates to the compensation of bid preparation efforts. Ho (2008) and Ho and Hsu (2014) game-theoretically study whether or not governments should provide a reimbursement for the SPVs that enter the tender and might spend a lot of money for the bid preparation, but that could lose the contract. The objective of the government is to incentivize the bidders to be willing to spend more on bid preparation. In a homogeneous setting in which all the features of the bidders are identical, Ho (2008) advises against compensation but this view is nuanced in the later study of Ho and Hsu (2014) that accounts for a heterogeneous bidding setting.

#### *2.2.5.3 Prequalification and preferred bidder selection*

Not every contractor that has shown interest in a particular PPP project will be allowed to enter the final bidding stage. The public party will perform a prequalification. Academic coverage of the prequalification question is scarce though. Doloi's (2009) survey and the subsequent linear regression and principal component analysis bring seven determinants for prequalification at the surface. Apparently, lowest price is not an indication for success, but the soundness of the business and workforce are more common. Additionally, Kumaraswamy et al. (2007) presume relationally integrated teams as a predictor for project success. But, shouldn't it be questioned then that it is hard to get into the market given the reliance on past performance and organizational capabilities? Russell (1996) acknowledges this issue and believes that the inexperienced candidates or these without good financial records should be screened instead of throwing their proposals in the trash can.

Also the literature on selecting the preferred bidder in the final bidding stage has been rather limited. Zhang (2006[a,b]) performed a questionnaire survey to understand how a public entity selects the winning bidder. 21 value contributing factors are found through factor analysis. In prior work, Zhang (2004) summarizes methods that have been proposed for contractor selection ranging from simple scoring, over NPV calculations, to the more dedicated Kepner-Tregoe method based on decision matrices.

#### *2.2.5.4 Pre-tender research by the contractor*

Contractors need to carefully prepare the bid proposal by looking into innovations and by making accurate cost estimations. While the risk identification and assessment issues are well-discussed in the literature, academics stay rather vague when it comes to the amount of pre-tender investment efforts that is necessary. Aibinu and Pasco (2008) empirically conclude that, in a general construction context, the accuracy of the bids is often determined by the project size. Smaller projects seem to have a larger bias in relative terms. Unfortunately, they add to this observation that the accuracy has not changed over time. Not only the financial aspects are important to determine the viability, but typically a multi-criteria assessment is required (McCowan and Mohamed 2007).

Looking at the innovation efforts, Rangel and Galende (2010) found in a study of the Spanish PPP market that innovations are not an intrinsic characteristic of PPPs. Roumboutsos and Saussier (2014), on the other hand, conclude that contractors have an incentive to invest in low-risk innovations that possibly affect cost savings during construction and operation.

These pre-tender research efforts come at a cost and could become an important barrier to entry, tempering the competition in the market (Carrillo et al. 2008). Zou et al. (2008) identified the lack of competition as one of the important reasons for failure. McAfee and McMillan (1986) and Zitron (2006) support this idea and argue that a lack of bidders could disrupt the value for money concept. However, the authors add that a large number of bidders might force strong bidders to be reluctant to bid due to the reduced probability of winning with a high sunk cost of the consultancy and tendering expenses. This drives the contribution of this dissertation and the paper of Ho and Hsu (2014) claiming that bid cost reimbursements might be beneficial.

#### *2.2.5.5 Contractor bidding*

Pricing a PPP contract is a challenge, because a regular price list is not sufficient in this environment. Contractual peculiarities like the risk allocation, the government guarantees and the length of the concession receive particular interest in the construction literature. Only a restricted number of quantitative techniques have been used by researchers in construction projects like simulations (e.g., Zhang 2009), regression models (e.g., Ngee et al. 1997), fuzzy logic (e.g., Ng et al. 2007[b]), social marginal cost pricing (e.g., Evenhuis and Vickerman 2010, Macário 2010) and financial methods (e.g., Shen et al. 2002, Cheng and Tiong 2005). The fact that a financial analysis based on the internal rate of return (IRR) or the net present value (NPV) is not really straightforward, is shown by Chiang et al. (2010). The long term aspect and the cash flow profile of PPP projects demand NPV-consistent IRR methods. A completely different approach is the one of Xu et al. (2012) that relies on information of the past to set the price by means of a system dynamics model that considers the complicated and interrelated structure of the pricing parameters.

Governmental interventions and their implications on the risk and pricing structure continue to receive a lot of attention in the academic literature. Fishbein and Babbar (1996) classify governmental support systems in eight categories. The government will install these support systems in order to provoke larger interest in a risky project. Such governmental support systems need to be reflected in the bid and accordingly need valuation. Uncertainty about future traffic revenues has been acknowledged as one of the most crucial risks in transportation PPPs. The minimum revenue guarantee is a common way to put a cap on the risk that has to be accepted by the private entity, but calculating the value of this guarantee is not possible with the traditional NPV approach (Liu and Cheah, 2009). Several authors rely on the theory of real options to attach an added value to these governmental policies (e.g., Cheah and Liu 2006, Wibowo et al. 2012, Carbonara et al. 2014). Liu and Cheah (2009) and Iyer and Sagheer (2011) classify the proposed methods in different categories: for discrete time, the multinomial lattice approach is used and for continuous time situations, one can develop closed form equations (to a limited extent), stochastic differential equations and simulation models. Brandao and Saraiva (2008) claim that the minimum revenue guarantee should only be included in high-risk projects. They assume a geometric Brownian motion (i.e., revenue is always positive and volatility is constant over time) and a series of European options with maturities between one year and the end-of-life time. Cheah and Liu (2006) also consider the other end of the spectrum. If traffic demand would exceed an agreed level, the government should come into play by increasing taxes or another way of pruning away excessive revenues. In short, the guarantee adds value, so the maximum transfer price should increase or the upfront price decrease and the cap structure involves savings for the government leading to the acceptance of a lower transfer price or a higher upfront price.

Other peculiarities or flexibilities to be taken into account are for instance the valuation of the option to expand or to abandon a project (Huang and Chou 2006, Huang and Pi 2009) and of the managerial flexibility to adapt the operational strategy or the facility given the contemporary condition of the infrastructure under study (Arboleda and Abraham 2006). A Markov chain stochastic process is used to model the deterioration process of infrastructures. When the condition of an infrastructure system is worse than expected, one should allocate more resources to the maintenance.

When the government intervenes with a regulation policy by putting a floor on the capacity of the road or a cap on the toll charges, the effect should be carefully investigated (Yang and Meng 2000, Chen et al. 2006). Subprasom and Chen (2006) developed a genetic algorithm and conclude that a combination of toll charge and road capacity regulations positively influences social welfare, but that the government should look after the financial viability of the project. Additionally, these governmental support systems have an impact for the financiers. Relying on the Capital Asset Pricing Model analysis, the cost of debt is proven to decrease through the use of a guarantee, while a direct cash subsidy increases the cost of equity because of the decline of depreciation tax shields (Wibowo 2006).

The concession period (i.e., the construction duration plus the operation duration) is a particular determinant upon which the government can also base its preferred bidder qualification, because this could increase efficiency (Zhang 2009). The length of the concession period is also a kind of risk management mechanism. Both the public as well as the private party have opposite aims: the contractor or concessionaire wants a reasonable return and the government wants to avoid excessive returns and hopes to reclaim the infrastructure at a suitable point in time (Ng et al. 2007[b], Zhang 2009). Zhang (2009) adds the incentive compatibility constraint that the concessionaire should act in the interest of the government and he makes the length of operation fixed, while the length of construction is variable.

Different methodologies are used to strive for a win-win situation: Ng et al. (2007[b]), Zhang (2009) and Carbonara et al. (2014) apply a Monte Carlo simulation-based approach, while Shen et al. (2007) rely on bargaining game theory.

The last determinant, and maybe the most important one from a contractor's point of view, is the mark-up. The literature has not extensively covered this problem in a PPP context. Iyer and Sagheer (2012) recently studied Indian BOT projects and identified two decisions to be made: the identification of the appropriate grant (i.e., the bid price) and the debt-equity mix. A genetic algorithm derives a Pareto optimal set for a bi-objective optimization model that maximizes the profitability and the bid winning potential. Disregarding some exceptions (e.g., Ho 2006, Iyer and Sagheer 2012, Xu et al. 2012, Ho and Hsu 2014), the vast majority of the investigated PPP studies does not take competition into account in the price determination. Also the contractors' heterogeneity is often overlooked, while experimental studies preach against the homogeneity assumption in the construction field (Oo et al. 2010).

#### *2.2.5.6 Risk identification, assessment and allocation*

Another procurement step that has already proven its exigency is risk management. Al-Bahar and Crandall (1990) define risk as "the exposure to the chance of occurrences of events adversely or favorably affecting project objectives as a consequence of uncertainty". Consequently, risk is a function of the uncertainty of an event and the potential loss or gain resulting from the event. Gruneberg et al. (2007) attribute the origin of risk in PPPs mainly to the longer term commitment. Grimsey and Lewis (2002) underline that the risk in a PPP project is mainly due to the complexity of the arrangement itself.

The study of Zwikael and Sadeh (2007) reveals that the quality of risk management planning has a positive impact on success measures like customer's satisfaction and technical performance. Planning involves several steps that can be summarized as follows: risk identification, risk analysis and evaluation, risk response management and risk system administration (Al-Bahar and Crandall 1990). Therefore, risks are not only to be considered upon negotiation of the contract, but risks should be monitored during the life cycle of the project, so that risk devolution from the private to the public party is prevented (Zou et al. 2008, Monteiro 2010). Fischer et al. (2010) propose an integrated risk management system for PPP projects in order to obtain this.

Value for money is a common identifier for analyzing PPPs. The cost of a PPP to the government is compared to that of a hypothetical counterfactual, the so-called public sector comparator. There is a lack of accurate information about the present conditions, the future and the implied social cost of the project. Moral hazard and adverse selection troubles are even harder to identify. The competitive tendering procedure is already a way to circumvent cost uncertainty, but prudence is in order. The risk of contracting has been discussed earlier, but also the nice sounding adagio “allocate the risk to the party that is most capable to deal with it” is not always a bed of roses. Monteiro (2010) reports that incentive schemes that align the private interest with the public interest can bring solace. These may also overcome problems of quality dilapidation of the infrastructure that would fall at the government’s expense due the so-called lock-in effect. Since the risk transfer is the greatest value for money driver (Jin 2010), an improper risk allocation may lead to the harmful value-deteriorating renegotiations of the contract (Marques and Berg 2011, Chang 2013[b], Cruz and Marques 2013[a]).

Both empirical as well as non-empirical research about risks in PPPs have been performed. Case studies give management insights into which risks to take into account and how certain risks influenced the success of a project. These case studies have the opportunity to show positive (e.g., Abednego and Ogunlana 2006) and negative (e.g., Sobhiyah et al. 2009, Chang 2013[b]) experiences in the allocation of risk. The results of these case studies, interviews and surveys often generate a risk allocation matrix (e.g., Ke et al. 2010). These matrices offer guidelines to project managers and governments to set up a risk allocation method in this particular case. Unfortunately, the qualitative empirical studies often lack the possibility of generalization to other PPPs. Hence, a careful analysis of the peculiarities of a certain PPP project is essential.

Researchers published risk classification schemes and all-encompassing lists of possible risks. Grimsey and Lewis (2002) define global and elemental risks. Other authors and institutions apply classification schemes depending on the features of the contract (e.g., Loosemore 2007, Monteiro 2010). Li et al. (2005) classify risks in three levels: the macro level with exogenous risks occurring outside the project (e.g., terrorism, studied by Boin and Smith (2006) or the recent financial crisis, studied by Regan et al. (2011)), the meso level for risks occurring within the boundaries of the project and the micro level risks due to inherent differences between the public and private entity. Chiara and Garvin (2008) talk about aleatory risk that is inherently present and that cannot be reduced and epistemic uncertainty that can be reduced as more relevant information gets collected. Jin (2010) applies a process point of view. He sets up a risk breakdown structure with three super-categories: risks mainly occurring in the development phase, risks in the operation and transfer phase and lifetime risks. Iyer and Sagheer (2010) look at the interactions among risks and determine the (in)dependency of certain risk factors. Nonetheless, whatever classification scheme is applied, a whole-life-cycle assessment needs to be made and risks of the project itself as well as exogenous risks should be identified. Of course, one only deals with perceived risk from a certain point of view, because every stakeholder will have its own interpretation and estimation of the risk (Jin and Doloi 2007, Roumboutsos and Anagnostopoulos 2008, Wibowo and Mohamed 2010). That is another motivation to focus on an integrated system and a continuous monitoring of the project risks.

After the identification of the PPP project risks, one needs to analyze the impact of the risk. Grimsey and Lewis (2002) list the distinct methodologies for the different stakeholders in the project. The procurer of the project will look at net present value calculations and he should perform the necessary sensitivity analysis. The sponsor will evaluate the impact of a certain risk on his return. The downside and upside of the different variables are analyzed, simulation exercises can be performed and the impact on the internal rate of return is estimated. More recently, Chiara and Garvin (2008) implemented the evolution of risk over time, since for some risks (i.e., epistemic uncertainty), it can be possible to learn over time. Some researchers rank the risks in a particular order, which is somewhat in between identification and assessment. An example is the research by Li and Zou (2011) that uses fuzzy AHP procedures to compare risks based on expert judgments.

Some authors only study the assessment of one particular risk. Kong et al. (2008) evaluate credit risk for project financing. Kokkaew and Chiara (2010) focus on completion risk where activities are correlated and they extend the stochastic critical path method with the envelope method in order to model managerial corrective actions. Raisbeck (2008) studies the design risk that should be borne by the contractor. Design risk deals with the question whether the design can be constructed on time and whether it will meet design requirements. The traffic revenue risk mitigation in real option theory terms has been discussed in Section 2.2.5.5, but a quantification is also proposed by an annuity model in Singh and Kalidindi (2006).

Risks do not occur in isolation and could be correlated. Iyer and Sagheer (2010) have acknowledged this and try to model the hierarchical structure of risks based on a reachability matrix that structures the interdependencies of the risks. Similarly, Thomas et al. (2006) use fault tree analysis and causal relationships with fuzzy possibility theory in order to structure the risks that might lead to the failure of a project. Ng et al. (2010) model the aggregate risk impact on the equity return in concessions by means of simulation.

The theory generally prescribes to allocate the risk to the party that is best able to manage it. Medda (2007) developed a theoretical allocation model of risks in transport PPPs. The author relies on game theory and considers the settlement between the public and private partner as a bargaining game or final offer arbitration game in which two agents compete to achieve the most reasonable offer. Lam et al. (2007) use a quantitative approach in a general construction context. The goal of risk management is seen as the minimization of the total cost of a project's risks. The authors use fuzzy set theory. Fuzzy logic is applied to transform linguistic variables into fuzzy subsets in order to execute fuzzy mathematical operations. Afterwards, the fuzzy outcomes are translated into understandable linguistic decisions. Xu et al. (2010) developed a similar technique in a Chinese context. A number of authors rely consistently on economic theory to explain the efficient risk allocation principles in PPP contracts on a cost-benefit basis: transaction cost economics (TCE) and the resource-based view (RBV) (Jin and Doloi 2008, Jin 2010, 2011, Jin and Zhang 2011). Transaction costs are the costs of running the economic system and TCE assumes that agents are not entirely rational but often act with self-interest. This opportunistic behavior comes at a cost. RBV, on the other hand, explains the heterogeneity among bidders. Every competitor has organizational capabilities that cannot be substituted nor imitated. These capabilities should influence the allocation of risks among parties. Five characteristics can be identified: a private partner's risk management routines, the cooperation history, risk management commitment, environmental uncertainty and the risk management mechanism.

Other risk allocation principles are often qualitative and rely on expert judgment. An easy practically applicable tool are the risk matrices. In a risk matrix, the role of each stakeholder in the mitigation of the risk is defined. Ng and Loosemore (2007) list the necessary conditions in order to allocate the risk to a certain party. Li et al. (2005) propose a clear allocation: the public sector should carry site availability and political risks and the private sector should take care of the majority of project risks, while relationship risks, force majeure risks and the risk of legislation changes should be shared. Chan et al. (2011) allocate most systematic risks (i.e., legal, political and social risk) to the public side, project and economic risks to the private side, while sharing the environment risk. So a clear consensus is not really present. Ng and Loosemore (2007) underpin a major limitation of such straightforward policies: risks must be identified, managed and monitored on a project-by-project basis.

Despite the theories, the adagio of attributing the risk to the party best able to manage it, often fails. In the end, the risks are often transferred to the government (i.e., the taxpayer) or the customer (Baeza and Vassallo 2010, Marques and Berg 2011, Vassallo et al. 2012). De Palma et al. (2009) additionally claim that the principal-agent problem and the asymmetry of information leaves room for opportunistic behavior that makes the risk allocation exercise even harder.

The next issue is the risk valuation in monetary terms, because taking extra risks mostly implies extra compensations (Gruneberg et al. 2007). How should a private party determine the value of the appropriate risk premium? Eriksen and Jensen (2010) warn for the fact that asymmetric information is a threat for the acceptable risk premium, leading to an excessive contractor compensation. They use the Capital Asset Pricing Model to calculate the risk premium, where the total return is composed of the risk free rate plus a premium. The discussion of the valuation of the government's guarantees and flexibility measures, that are in fact a mechanism to reduce the risk of revenue-based PPP schemes and that are inherently an intelligent way to properly allocate the risk, have been discussed in Section 2.2.5.5. Further risk compensation calculations in the particular PPP context are lacking.

#### *2.2.5.7 Governance*

After the deal is signed and all contractual responsibilities are divided, the contract needs to be governed in order to guarantee the efficient and viable execution. The majority of *ex post* studies bring governance structures at the surface that contributed to the success or failure of PPP projects (Section 2.2.5.8). The PPP governance process entails two subheadings: governance of the project execution which is merely borne by the private sector and the governance of relationships (i.e., contractual and stakeholder management).

The PPP-specific literature about the project execution is narrow which could mean that the theories from the project management environment might be extended to PPP projects. Kokkaew and Chiara (2010) apply a stochastic critical path envelope method on a build-operate-transfer project. Yuan et al. (2010) consider the execution phase and how to control the interacting variables taking into account the numerous stakeholders. The practical execution or planning of operations seems to be a minor issue than governing the contract and stakeholder management.

In this vein, Robinson and Scott (2009) make a summary of what it involves to set up a good governance structure from the public perspective. A clear output specification and cancelling out subjectivity is the start, but is often the most difficult task. A transparent performance monitoring system is the second element. Thirdly, one should think about a well-suited payment mechanism. A partnership environment should be established (Robinson and Scott 2009) that moves towards relationship management with care for each other’s culture, system and procedures (Smyth 2008).

Contract governance evidently intertwines with the initial contract structure and procurement mechanism of Section 2.2.5.2. Abdul-Aziz (2012) identifies three types of governance structures. First of all, market governance is a loose form that is output-oriented. Competitive bidding hopes to create suitable incentives. Of course, these output and performance specifications should be mutually accepted, as well as the incentive or punishment mechanisms (Ng and Wong, 2007). Secondly, bureaucracy governance is rather strict, as specified norms and standards are the key characteristics. Anything in between is a kind of hybrid form often materialized under a flexible contracting form. Although informal relationships are sometimes seen as more effective than formal contracts (Jones and Noble 2008), empirical results in Malaysia for instance show that the hybrid form and the bureaucratic form are apparent (Abdul-Aziz 2012).

Relationship management between the government and the SPV, but also within the SPV is a key concern in PPPs. Barretta et al. (2008) claim that the success of a project depends on the established trust. The researchers note four levels of trust: trust in the system, contractual trust, trust in competences and goodwill. Smyth and Edkins (2007) keep it at two types of trust: self-interested trust (i.e., a win-win type of trust) and socially oriented trust.

Taking care of all your stakeholder relationships is a daunting task and experiences are mixed (De Schepper et al. 2014). The first step is to determine who your most important stakeholders are. Chowdhury et al. (2011) offer network theory as an aid to structure the PPP project's stakeholders and how the agreements between the different parties are settled. A second aspect of stakeholder management is a clear communication and a common understanding by sharing the same semantics (El-Diraby and Gill 2006). All stakeholders have different values. Bringing these values together and governing that everybody remains pleased is a challenge. Yuan et al. (2010) try to integrate the stakeholders' perspectives by means of two methodologies: fuzzy information entropy and an enhanced TOPSIS (i.e., technique for order preference by similarity to ideal situation) method. The former is based on the stability of a solution and the weight of each stakeholder group. The latter tries to set up a performance level that everybody can accept and that is as close as possible to the ideal situation and as far as possible from the negative ideal situation.

The problems of opportunistic behavior have implications on the governance structure. Financial renegotiations can often not be circumvented. The government will decide whether or not to rescue the contractor. Ho (2006) developed a game-theoretic claim decision model. He starts with the observation that contracts are being renegotiated and by modelling this dynamically the option to renegotiate will return to opportunistic bidding behavior. The literature on renegotiation issues is receiving more attention which could mean that hold-up problems and lock-in issues are surging (e.g., Chang 2013[b], Cruz and Marques 2013[a], Javed et al. 2014, Xiong and Zhang 2014).

#### *2.2.5.8 Ex post analysis and key performance indicators*

The papers that are categorized in this class are different in nature. *Ex post* studies concern experiences from past projects or from recent region-specific experiences. Papers that handle key success factors go beyond an evaluation and state clear generalizations of the case studies or summarize quantitative practitioners' survey studies.

PPP projects are relatively recent phenomena and qualitative research efforts are necessary to build a knowledge database with good and bad practices. Several case studies emphasize the positive experiences that could become prototypes for future projects: e.g., Smith et al. (2004), Jefferies (2006), Chen (2009), Raisbeck et al. (2010), Zheng and Tiong (2010), Papajohn et al. (2011). PPPs can offer an integrated solution and can rely on the expertise from the private sector, but evidently, for some countries the attractiveness factors will be different than in other countries.

Negative encounters that often result from challenges that have been discussed in earlier sections are also reported: renegotiation problems, lock-in effects, inappropriate risk allocations or obstructions due to political disinterest.

A set of ex post evaluations critically looks into the key value for money drivers. Innovation and an increase in efficiency are key drivers for PPP contracting. Unfortunately, Leiringer (2006) and Rose and Manley (2012) warn for impeding factors that have prevented contractors to be innovative and Pollock et al. (2007) argue that there is no evidence base to conclude that PPP contracting has reduced cost and time overruns. Another key driver is the risk transfer. Pollock and Price

(2008) question the evidence base upon which it was decided that risk transfer has led to value for money.

While the majority of studies considers transportation infrastructure projects, it is often discussed that PPPs are even harder and more costly to implement for social infrastructure projects, like healthcare projects (Shaoul et al. 2008, Vecchi et al. 2010, Cruz and Marques 2013[b]), schools (Reeves and Ryan 2007) or prisons (Jefferies and McGeorge 2009). A better training for assessing the value of the projects and the included risks might be convenient (Cuthbert and Cuthbert 2010).

The next step is to translate the good and bad practices into key success factors. A classic list can be found in Jefferies (2006). In a more recent study, Yuan et al. (2012[a]) develop 41 performance indicators that contribute to the success of PPPs. These are obtained by means of surveys and a confirmatory factor analysis. Among some specific issues, transparency and an appropriate legal framework are regularly reoccurring. Also external factors contribute to project success. Tserng et al. (2012), for instance, evaluate the positive effect of an external PPP unit to promote and help implementing PPP units. Of course, external factors are not evident to monitor. A stable macroeconomic environment but also a nationally stable political situation contribute to removing the inhibitors of PPP agreements (Chan et al. 2010[a], Wibowo and Alfen 2014). Moreover, force majeure risks like terrorism (Boin and Smith 2006) or the financial crisis risk (Regan et al. 2011) are also beyond control and raised needs for new governance and policy measures.

## 2.3 Takeaways from the literature on bidding for infrastructure projects

The PPP construction literature offers some important insights into contractor bidding, but a lot of competitive aspects are overlooked. The emphasis is mainly on the one-to-one negotiation between the public and the private entity, while general bidding models like the one of Ho (2008) or the one in this dissertation are scarce.

This section concisely constructs a bridge with bidding models in the traditional infrastructure construction literature. The study of the aforementioned construction journals proposes a three-dimensional classification to map the characteristics of the bidding models:

- Homogeneous versus heterogeneous bidders;
- Once-only versus repetitive projects;
- Selection based on price versus based on a multi-criteria approach.

While most PPP studies look at contractor bidding aspects from a homogeneous perspective (e.g., Ho 2008, Shen et al. 2007, Tserng et al. 2012), other approaches fundamentally take heterogeneity into account (e.g., the risk allocation studies of Jin (2011) by means of the resource based view). Oo et al. (2010) experimentally concluded that bidders are essentially heterogeneous. In the non-PPP literature, this heterogeneity aspect found resonance in the bid/no bid decision setting of Bageis and Fortune (2009) or the empirical competitor analysis approaches of Tan et al. (2010) and Yuan (2012) that rely on past bidding data.

The analysis of past bidding behavior is of course only possible in a rather repetitive setting, while megaprojects, like PPPs, are often once-in-a-career decisions (Flyvbjerg et al. 2009). Nevertheless, most bidding studies in the construction literature assume repetitive behavior (e.g., Skitmore and Runeson 2006, Christodoulou 2010, Kim and Reinschmidt 2011). The initiators of the competitive bidding literature are Friedman (1956) and Gates (1967), but the literature dispersed and different methodologies are introduced to deal with more complex bidding environments. These methodologies range from simulations (e.g., Cagno et al. 2001), over multi-criteria optimization models (e.g., Iyer and Sagheer 2012) to exotic entropy-based methods (Christodoulou 2010).

The bidding strategy of the contractors is naturally dependent on the decision mechanism of the contracting authority. PPPs typically require multi-criteria decision making, since this is a perilous choice for the government in the case of contract durations of over thirty years. In traditional contracts, the lowest bid usually wins the tender. However, there are also price-based alternatives like the below average method in which the bidder that bids just below the average bid is awarded the contract (Ioannou and Awwad 2010). The multi-criteria assessments all fall under the umbrella of most advantageous tendering (e.g., Perng et al. 2006, Tzeng et al. 2006) and a plethora of methodologies exists: multiple regression, data envelopment analysis, multi-attribute utility theory, cluster analysis, fuzzy theory, and analytical hierarchy process are only some of the methodologies in the landscape (Darvish et al. 2009). Zhang (2006[a,b]) lists the methodologies in the PPP context. Sometimes the selection is in several stages: typically first a prequalification stage is based on the quality of the contractor and afterwards the lowest bid gets priority (Abudayyeh et al. 2007).

Nonetheless, these scoring mechanisms and the decision mechanism itself is of utmost importance. It is especially necessary to mitigate the risk of opportunistic bidding behavior. Bidders can bid too low in order to stay in the market. Also misinterpreting flexibility options or renegotiation opportunities could be harmful as they lead to beyond contractual rewards that might inflate opportunistic bidding behavior (Lo et al. 2007, Mohamed et al. 2011) or unbalanced bidding (Wang et al. 2006, Arditi and Chotibhongs 2009). Transparency should overcome most of the principal-agent issues and the government should minimize the variability among contractors through clear information provision and communication (Müller and Turner 2005, Skitmore 2008, Flyvbjerg et al. 2009).

Consequently, the general infrastructure bidding literature shapes a broad view on different bidding settings. Nevertheless, the peculiar characteristics of the complex PPP environment were repeatedly underlined, which means that one should beware of blindly transferring a methodology or setting to the PPP context. As a result, this dissertation claims a spot in the field by focusing on a heterogeneous setting in a limitedly repetitive environment. While PPPs actually require a multi-criteria approach, the model in this dissertation accounts for the lowest price mechanism under the assumption that prequalification has been performed in an earlier stage. However, the model does allow for a monetary correction of the bid price given the quality of the bidder and the proposal (Section 3.2).

## 2.4 Conclusion

The PPP literature has been extending since the introduction of PPP projects in the early nineties. The country- and sector-specific nature of the project is key so prudence is in order before generalizing findings and experiences. Nevertheless, this chapter gave a general overview of the contemporary topics. The focus of the dissertation is on the procurement stage of the PPP process. These negotiations often take a very long time. The engagement in this long-term commitment is daunting and risky. As a result, the importance of the tendering procedure cannot be overestimated as the project might develop as a rollercoaster after the contract is signed and both parties might be locked in and might become the victim of uncertainty and of their own relationship. A divorce without huge opportunity costs in PPP contracts is often not possible, so planning and managing the marriage is vital.

A lot of the challenges draw back to the asymmetry of information. The incentives that are offered by the government can incur perverse incentives at the private side. Every policy measure therefore needs detailed and critical analysis. Opportunistic bidding behavior and excessive renegotiations are harmful. In the current literature, this holistic view is often overlooked. In several analytical approaches, only the private or the public entity is considered which renders the whole picture incomplete. Much effort should be put in this holistic view, especially in PPPs that move beyond a platonic execution of a project but that attain high value to partnership and efficiency.

The concept of risk management is known and is recognized by scholars and business people alike, but the active application of continuous risk management policies is not widespread. A wide range of methodologies have been developed, but it should be investigated how these methods can be implemented comprehensively. Perhaps neither the public party nor the private party wants to rely on simulations or possibly the quantitative models do not capture reality very well. Some quantitative methods exist, but a straightforward and easily implementable approach can still be developed, especially in how to incorporate positive and negative risks in a bid. Quantitative bidding models are scarce and the assumptions of the traditional construction literature are often not transferable to PPPs.

In conclusion, this dissertation adds to the PPP literature in the sense that it offers theoretical guidance in the procurement phase. The model studies the public-private relationship, but also considers the competition among contractors in a high-risk environment. Therefore, in terms of Table 2.7 and from the public angle, the dissertation is classified under the mechanism and contracting heading. From the private angle, the focus is on pre-tender research and contractor bidding. Moreover, since risk plays an important role in the PPP model, the results also add to the theoretical risk assessment literature. Consequently, due to its multi-faceted dimensions, we believe this dissertation's strength lies in the holistic view on high-risk projects between governments and private sector consortia.

# Chapter 3 Model and assumptions

This chapter introduces the model and assumptions that have been taken along the research project. The model results from a revision of the contemporary academic PPP literature, in order to grasp the main characteristics of the PPP procurement process. However, assumptions are necessary to reduce the level of complexity. Nevertheless, a collaboration with industry practitioners (e.g., contractors, investment companies, advisory firms and public institutions) has been installed with the purpose of guaranteeing that the simplifications would not downgrade the value of the model. Section 3.1 describes the general procurement framework. The general modelling assumptions that are consistent for all remaining chapters and that inherently drive the contribution of this dissertation are discussed in Section 3.2 and lead to the decision variables of Section 3.3. These essential determinants of the model are subsequently translated from a general level into an abstract analytical level. The overall theoretical model is described in Section 3.4 and the dissertation's implementation characteristics in Section 3.5.

## 3.1 The PPP procurement model

Disregarding some sector- and country-specific features, the PPP procurement process generally has two stages. After the public communication, consortia or special purpose vehicles (SPVs) that consist of designers, construction contractors, subcontractors, suppliers and maintenance companies can express their interest for the project. In the remainder of the text, we make abstraction of the internal structure of the consortia to which we refer as "a contractor or bidder". A prequalification mechanism shortlists a by the government defined number of contractors that are invited for tender. In practice, this number varies between two and four and in a rare case five bidders, depending on the jurisdiction, the interest and the complexity of the project. In the second stage, which our model represents, the shortlisted contractors independently develop a project proposal that includes among other things the design details as well as process, management and financial information and that meets the government requirements. Due to the long-term time span, the magnitude and the entailed risk of PPPs, a lot of effort needs to be put into these proposals. In order to develop a competitive yet profitable project proposal, each contractor may engage in research studies and legal advisory activities. These pre-tender research and development exertions come at a cost, but contribute to the quality of the proposal. Moreover, each contractor determines the required mark-up that accounts for the requested profit and the monetary mitigation of risk. The project information and the bidding environment information that consists of the number of bidders and their respective competitive positions affect these decisions. After the proposals have been received, the government grants the project to the economically most advantageous bidder based on the assessment of the cost and the quality of the submitted proposals.

## 3.2 General assumptions

The study of the academic literature together with the consultation of practitioners has led to a set of model characteristics and assumptions that differentiate the dissertation from the former (procurement) auction literature.

Contractors that are involved in the research project have confirmed that their bidding strategy is influenced by the consortium's risk attitude, its maturity in the market and the bidding environment (i.e., the number of competitors and their respective experience levels). Consequently, the PPP market is in general observed to be heterogeneous. Practitioners from both the public as well as the private angle distinguish inexperienced entrants from mature, well-established incumbent consortia. In an academic vein, Oo et al. (2010) experimentally conclude that bidders' bidding behavior is diverse. Therefore, a continuous experience scale has been introduced. A player $p$ has an experience level $e_p \in [0,10]$ which is an *ex ante* assessment (i.e., without taking investment into account) of how familiar a certain contractor is with a particular market and which could in practice easily be observed by the number of past projects within this specific field and within this particular jurisdiction. Sometimes, the country-specific nature of a project is of paramount importance so that project-specific knowledge does not suffice and the familiarity with a country, the credibility status or the available resources (e.g., a specialized drilling machine) could add to the experience level. As a consequence, consortia that have a mature position in a European market, might be perceived as an immature entrant in a Canadian market, due to the legal requirements or the lack of credibility. Including these asymmetries complicates the model, but is a major contribution to the existing bidding literature, that usually assumes symmetric players.

*Assumption 1: The bidding environment information that consists of the number of shortlisted bidders and their respective experience levels is common knowledge.*

Project costs can be represented by probability distributions that are defined by its parameters that are related to its expected value and its level of variability. Uncertainty in the project outcome and the project risks are aggregated and translated into a single measure: the variance of the expected project cost together with the associated bid probability density for each player. Complex or risky projects like toll roads or hospitals have wider distributions than social housing projects for instance. These distributions are dependent on the experience level of the bidder and the amount of money the bidder has invested in research.

The experience level of a player contributes in a two-fold way. First of all, more experience results in a direct cost impact because of economies of scale, efficiency gains and the familiarity with the market. Model-wise, one might say that the expected value of the cost probability density of a more experienced contractor is lower than that of his less experienced counterparts. Secondly, experience has a knowledge impact in terms of the accuracy of the estimated project cost.

Equivalently to the impact of the experience and in line with recent R&D research (Martzoukous and Zacharias 2013) and project management research (Lippman et al. 2013), a contractor's pre-tender investment contributes in two ways to the transformation of the cost curve. Pre-tender investment shifts the cost curve to the left due to innovative disclosures and efficiency gains, which results in a lower expected cost. Besides, the variance of the cost distribution decreases as investment leads to more accurate cost estimates. The variance of the cost probability distribution reflects the complexity or the risk of the project. For reasons of simplicity, risk is categorized in two types: an uncontrollable part that is the same for all contractors (e.g., force majeure risk, risk of contract renegotiation by the government or macroeconomic risk) and a controllable part (e.g., demand risk, project risk) that can be reduced or mitigated through the appropriation of experience or the performance of research investments. If a project has a fairly repetitive nature, experience is the main contributor to the uncertainty reduction, while if it is highly innovative, the investment is of paramount importance. In summary, this results in three assumptions.

*Assumption 2: The complexity or risk of a project is translated into the variance of the cost probability density and consists of a controllable part and an uncontrollable part.*

*Assumption 3: The more experienced a player is and the more a contractor has invested in pre-tender research, the lower the variance of the cost probability density (knowledge impact assumption).*

*Assumption 4: The more experienced a player is and the more a contractor has invested in research, the lower the expected project cost (direct cost impact assumption).*

The quantitative impact of assumption 3 for player $p$ is given by a fraction $\sigma_p^2$ and for assumption 4 by $g_p$. Assumption 5 relates to the belief that both contractors as well as the government are able to assess the degree of complexity of a project, based on for instance the available project information and similar previous experiences.

*Assumption 5: All participants know the general structure of the game and the distributional characteristics related to assumptions 2 to 4.*

In the modelling procedure, the government selects the lowest-bidding contractor. This might seem in contrast with the cost/quality trade-off that governments claim to make when assessing the proposals. Nevertheless, with a slightly different implementation, assumption 4 inherently also reflects the cost/quality trade-off: if the government would put a greater emphasis on quality and experience, the contractor's cost distribution shift would be more significant if he invests more in research or has more experience. That means that we inherently assume that the investment effort is a good proxy for the quality of the proposal. This relates to the cost adjustment implementation of Kostamis et al. (2009). In this vein, assumption 4 puts a monetary value on the preference for more qualitative bids or for more experienced contractors by rewarding them with a discounted bid. In the current model, assumption 4 reduces the expected project cost of the probability distribution, while the alternative interpretation would modify the bid probability distribution. Nevertheless, we believe that the bidding outcome is equivalent, so that this flexible approach validates the fact that the model's decision maker selects the lowest bidding contractor as the preferred bidder. Assumption 6 summarizes the government decision mechanism and accounts for the possibility that the government reimburses the losing bidders for their research efforts.

*Assumption 6: The government selects the lowest bidding contractor. If the government installs a percentage-wise bidding cost reimbursement policy, bid compensations are equally credited to all losing bidders.*

Last but not least, contractors are assumed to be risk-neutral and maximize their expected pay-off.

*Assumption 7: Contractors maximize their expected pay-off.*

The *ex ante* strategy model and the sequential strategy model of Chapter 5 and Chapter 6 respectively requires the introduction of three additional assumptions with respect to the multi-project setting. The pipeline concept is defined in more detail in Section 5.1.

First of all, we acknowledge the synergetic effects that result from executing multiple projects of a similar type. Basically, a contractor who wins a project moves towards a higher level on the experience scale, regardless of whether this project has been profitable or loss-making. Consequently, we assume that winning a contract may result in a knowledge and cost advantage in later tenders.

*Assumption 8: Winning a contract results in an experience level increase.*

An important assumption for the strategic model is related to the exogeneity of the bidding environment. In the entire project pipeline, no new players enter the game and the same set of players is considered for each project. In practice and in future models, randomly arriving contractors could be introduced. Nevertheless, the consortia within most PPP jurisdiction have a stable structure and the number of (sub-)contractors that is able to participate is low. Moreover, also the finite pipeline of projects is assumed to be common knowledge and, without taking experience and investment into account, all projects have a stochastically equivalent nature. This means that the common cost probability distribution parameters that are the same for all players are stable along the pipeline. Hence, the projects in the pipeline have the same type (e.g., all projects concern prison projects).

*Assumption 9: The project pipeline is commonly known and each project has the same risk and cost structure. The same set of bidders is considered for the entire project pipeline.*

A final assumption that is related to the dynamic modelling and that offers opportunities for extensions, concerns the budgetary and resource requirements. In practice, contractors claim that it is infeasible to simultaneously engage in a multitude of projects simultaneously because of the magnitude and the risk exposure. Nonetheless, because this dissertation only considers project pipelines of a limited finite nature, we allow bidders to execute all projects of the pipeline and therefore do not include capacity constraints.

*Assumption 10: Each player is assumed to be capable of performing all projects in the pipeline and has sufficient resources at his disposal.*

## 3.3 The decision variables

The setting is considered as a bi-level programming model. At the lower level, contractors are bidding against each other and simultaneously optimize their expected pay-off (assumption 7). A bidder's expected pay-off is dependent on the competitors' actions, which suggests a game-theoretic approach. In this vein, under the traditional rationality assumptions of game theory, the bidders arrive at a strategy equilibrium. This strategy equilibrium is dependent on the project characteristics and on the market structure. To a certain extent, the government controls the tendering procedure and may install policies that modify the resulting bidding equilibrium. As a result, the government acts as the decision maker at the upper level of the bi-level model.

### 3.3.1 Decision variables of the contractors (lower level)

The definition of the strategy depends on the model that we consider. Nevertheless, in essence, the decision variables are comparable for each of the settings. Basically, each shortlisted contractor makes two decisions for a particular project. On the one hand, the bidder determines the level of pre-tender research. This is the monetary effort that the consortium is willing to put into developing the project proposal and could consist for instance of consultancy costs, lobbying costs and design costs. It could also entail the cost to insure particular risks with a third party insurance provider. On the other hand, the contractor determines a mark-up percentage that is applied to the estimated project cost. The mark-up is a way to mitigate the remaining risk by setting a risk premium, together with a preferred profit margin. Since the contractor is never certain about the actual government cost, but only receives a signal to which he applies the mark-up, one might consider the investment and mark-up decision making for a particular project as a synchronized action, so that they are combined into a single partial strategy. As an example, consider the action 1% investment and 20% mark-up. The investment decision refers to 1% of a pre-set reference base (e.g., € 1,000,000), while the 20% mark-up is added to the estimated project cost.

A strategy in game-theoretical terms is more than combining these decision variables. A strategy prescribes the actions to take at each decision point of the game tree, or more correctly, at each information set of the game tree. The notion of information sets reflects the fact that a player might not know everything that happened "previously" in the game. "Previously" does not necessarily have a temporal meaning. In our setting, each player makes a decision for a particular project simultaneously. Consequently, a player does not know the strategy of the opponents and is therefore uncertain about the exact decision point he arrived at. An information set groups all these possible decision nodes. Nevertheless, a player does know at which information set he is. The combination of decisions at the different information sets determines a strategy. As a consequence, the interpretation of a strategy is different for the different subsequent chapters. In brief, Chapter 4 makes a single investment and mark-up decision, Chapter 5 makes an investment and mark-up decision in each *stage* of the game and Chapter 6 in each *state* of the game (see Section 3.3.1.1 to Section 3.3.1.3).

Disregarding the specific content of a strategy, we can represent a strategy for player $p$ as $s_p$. The vector that combines the strategies of the $P$ players is called a strategy profile $s = (s_1, s_2, \ldots, s_P)$. Each player optimizes his expected pay-off (that is explained in Section 3.4) and that is dependent on the strategies of the competitors. We represent the strategy profile of the opponents as $s_{-p}$. We define a (Bayesian) Nash equilibrium strategy profile $s^* = (s_1^*, s_2^*, \ldots, s_P^*)$ as the optimal strategy vector. For this combination of optimal strategies, none of the bidders has an incentive to deviate from his current strategy choice $s_p^*$, given the strategy combination of the opponents $s_{-p}^*$. With $\pi_p(.)$ the total expected pay-off function for player $p$, this is mathematically expressed as:

$$\forall p, s_p \in S_p\colon \pi_p\left(s_p^*, s_{-p}^*\right) \geq \pi_p\left(s_p\ , s_{-p}^*\right) \tag{3.1}$$

#### *3.3.1.1 Single-project model*

The game tree of Figure 3.1 is the representation of the assumed single-project PPP setting. According to assumption 1, the number of shortlisted bidders and their experience level is common knowledge for all players. We represent the experience level of player $p$ as $e_p$ with $e_p$ a value along the predefined experience scale with $e_u$ the number of experience intervals. The combination of experience levels is an experience vector $e = (e_1, e_2, \ldots, e_P)$ with $P$ the number of players in the tender. As this is common knowledge, we may define this experience vector as a proper subgame of the game tree. A subgame is referred to as a game within a game up to a particular point where the players know exactly where they are in the tree. Assume that a discrete number of experience levels on a scale from zero (i.e., no experience) to ten (i.e., maximum experience) is set up. A game with $P$ players and $E$ $(= e_u + 1)$ levels of experience would lead to $G = \frac{(P+E-1)!}{P!(E-1)!}$ subgames or bidding environments. The value $G$ results from the notion of a "combination with repetition". A strategy of this game would prescribe the decisions for each of the subgames. The experience vector is determined at the beginning of the game (in Figure 3.1 modeled by the node $N$ that stands for nature) and that is common knowledge for all players. Then players 1 and 2 make their combined investment decision and mark-up decision simultaneously. We assume that they can select these percentages from a continuous range of possibilities, which would result into an infinite number of choices, indicated by the arc between the two branches of the players' decision nodes. None of the players knows the decisions of the opponent, which is represented by the dotted line between the two nodes of player 2 in Figure 3.1 and which means that these two nodes are part of the same information set. Therefore, we rely on the notion of subgame perfectness (Gibbons 1992). A subgame perfect equilibrium is a refinement concept that limits the number of possible strategies that could be considered. A subgame perfect equilibrium prescribes the optimal behavior for each proper subgame of the game tree, i.e. for each possible experience vector. All contractors $p$ determine their optimal partial strategy $s_p^*$ for each subgame. The partial strategy $s_p$ is a combination of which percentage $i(s_p)$ with respect to an initial cost base $\mu$ is invested in pre-tender research and which mark-up percentage $m(s_p)$ is applied to the estimated cost. The combination of all these optimal partial strategies is the optimal strategy for the entire game. In the remainder of the text, we prefer the use of the term strategy to refer to a partial strategy, because we will always optimize the decisions for a given vector $e$ of experience levels (i.e., a subgame).

#### *3.3.1.2 Ex ante model*

In the *ex ante* model that is dealt with in Chapter 5, a (partial) strategy consists of a larger number of decisions or actions, because this chapter introduces the concept of a project pipeline. Often governments have a project agenda, so that the contractor's decision making process is not just related to a single-project decision. The government initiates and communicates the project pipeline. We assume that this pipeline is trustworthy, that its projects are stochastically equivalent and that it is not subjected to considerable changes. The tendering processes are often long or overlapping and sometimes contractors need to make investments for future projects. Therefore, in this *ex ante* framework, there is no immediate information revelation so that contractors cannot change their strategy along the line. Consequently, each bidder makes the investment and mark-up decisions upfront which makes it a simultaneous game. A graphical representation of the *ex ante* game looks equivalent to Figure 3.1. This also means that the *ex ante* strategy is based on the expected beliefs whether one will win or lose a project before moving to the next project in the pipeline. Alternatively, the fully sequential model of Chapter 6 builds a strategy pattern that prescribes the strategic behavior first for the initial project and would then determine the strategy for the second project for each possible outcome (i.e., for each possible winner) of the first project.

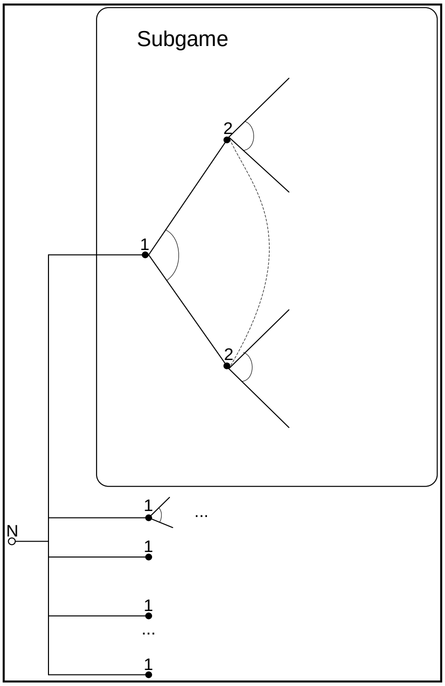


Figure 3.1 Game tree for a two-player game

It is assumed that the number of bidders is expected to be the same over the course of the projects (assumption 9). Consequently, the initial experience levels of the shortlisted bidders are common knowledge. A subgame is again represented by an experience vector $e = (e_1, e_2, \ldots, e_P)$. In subgame $e$, contractor $p$ determines the optimal strategy $s_p^*$ for the entire project pipeline with $Z$ projects. An *ex ante* strategy $s_p$ is composed of two decisions for each project $z \in \{1,2,\ldots,Z\}$ in the pipeline: an investment decision $i(s_p^z)$, that is expressed as a percentage of an initially set project cost base, and a mark-up decision $m(s_p^z)$, that is expressed as a percentage value and that is applied to the estimated project cost. In this vein, $s_p^z$ refers to the decisions (or actions) within strategy $s_p$ that are related to stage $z$. The full strategy $s_p$ for player $p$ is thus represented by a vector $s_p = \left(i(s_p^1), m(s_p^1), i(s_p^2), m(s_p^2), \ldots, i(s_p^Z), m(s_p^Z)\right)$.

#### *3.3.1.3 Sequential model*

The sequential model allows for a modification of the actions along the pipeline. Hence, a strategy in this model has a more complex structure and the notation in Chapter 6 diverges from its preceding chapters. Given is a commonly known project sequence $\mathcal{Z} \coloneqq \{1,2,\ldots,Z\}$. We want to identify the strategy equilibrium of the subgame $e = (e_1, e_2, \ldots, e_P)$ that defines the initial experience setting of the players of the game. This setting is a stochastic game, as has been introduced by Shapley (1953). A stochastic game is a finite or infinite dynamic game that is played by one or more players with probabilistic transitions between a finite number of states. In this setting, the players are assumed to be long-lived and have unlimited capacity to perform all the projects of the pipeline. In each stage of the sequential game, the contractors want to optimize their expected pay-off which consists of the instantaneous pay-off of the current stage and an expected continuation value of the pay-offs in future stages. We are looking at Markov strategies and identify a Markov perfect equilibrium (MPE) as presented by Maskin and Tirole (2001). This is justified under the assumption that the current play is only influenced by the expected pay-offs of future projects on the one hand and the state variable on the other hand. For a given project or stage $z \in \mathcal{Z}$ from the sequence, we determine the current state $\theta^z \in \Theta^z$ as the combination of the current experience levels and the number of remaining projects in the sequence $Z - z$ or $\theta^z = (e, Z - z)$. The history $h_z$ at stage $z$ is summarized into this state variable. Consequently, we assume that past investment and mark-up decisions solely impact the current behavior by having won or lost the tender. For a given state, a set of actions $\mathcal{A}_p^z = \mathcal{A}_p^z(\theta^z)$ is available for each player. We assume that the set of available actions is the same in every state of the game, so that we can refer to the set of actions as $\mathcal{A}_p$. An action $a_p^z$ in a state $\theta^z$ is composed of two elements: the amount of pre-tender investment $i(a_p^z|\theta^z)$ a player $p$ is willing to adopt and which is expressed as a percentage of an initial cost base equal to 1 and the mark-up $m(a_p^z|\theta^z)$ defined as a percentage that is applied to the estimated project cost. Consequently, a strategy $s_p$ for player $p$ prescribes which actions to take in each of the possible states of $\Theta^z$ for all $z \in \mathcal{Z}$ that could occur in the game.

### 3.3.2 Decision variables of the government (upper level)

Moving the scope to the public sector, the government has the ability to decide on particular dimensions of the bidding process. The government is the principal in shaping the bidding environment and is in fact able to influence the equilibrium bidding behavior described as equation (3.1). Firstly, the government determines the number of candidate concessionaires $P$ who are up for the final bidding stage. Secondly, the public sector can control some of the parameters related to assumptions 3 and 4 to a certain extent. On the one hand, the public institution oversees the decision mechanism for the selection of the preferred bidder and could therefore opt for a lowest cost perspective, a maximum quality perspective or a trade-off between monetary and qualitative aspects. On the other hand, governments initially determine a proposal that concerns the risk allocation between the public and private sector. The type and the amount of risk that is transferred to the private sector has corollaries on the bidding behavior. Thirdly, a topic of major concern is the fact whether the government should reimburse a fraction of the pre-tender research cost to any of the losing bidders so as to increase the investment incentives of the candidate contractors. Last but not least, the concept of the project pipeline is introduced. The government could launch several projects so that bidders believe that the tender is not a single-shot game, but that there are future opportunities available.

The final objective of the government may have multiple dimensions. First of all, from a purely monetary perspective, the public sector could want to minimize the total public expenditures. From a more qualitative perspective, they might be favoring a levelled playing field that maximizes the competition in the market. That could be beneficial if the government wants to cement a competitive market with a sufficient number of players in the long run. Another objective might be to reduce the probability of default or renegotiation by the preferred bidder. As it is a daunting task to gather all these dimensions within a quantitative objective function, we prefer a Pareto approach to discuss the impact of the available intervention policies on the public objectives. The decision variables that the government is able to tune do not always point towards a dominant decision in the sense that it positively influences all government's objectives. Hence, it is in our goals to come up with non-dominated policies that, together, form an efficient frontier. The government thus still needs to define the weight they attribute to each objective and trade off the proposed policies.

## 3.4 Theoretical foundation for the expected pay-off

Theoretically, the pay-off calculations for the subsequent chapters all rely on the same theoretical philosophy. This section analytically describes how to arrive at the pay-off for a particular project, further called the instantaneous expected pay-off. Basically, we make abstraction of the possibility of a pipeline, so that we only consider a single project and do not account for future values. However, the future value is in fact a linear combination of instantaneous pay-offs. In order to avoid confusion and to generalize the approach for all subsequent chapters, we use a slightly different notation: $\bar{e} = (\overline{e_1}, \overline{e_2}, \dots, \overline{e_P})$ for the intermediate experience levels at this particular stage and $\bar{s} = (\overline{s_1}, \overline{s_2}, \dots, \overline{s_P})$ referring to these decisions of the strategies that relate to this particular stage or state of the game. Moreover,

$\bar{s_p} = \left(i(\bar{s_p}), m(\bar{s_p})\right)$ states the investment and mark-up decision for the project under study.

For a given experience vector $\bar{e}$ and a strategy profile $\bar{s}$, we derive the instantaneous expected pay-off vector $\rho = \left(\rho_1(\bar{s}|\bar{e}), \rho_2(\bar{s}|\bar{e}), \dots, \rho_P(\bar{s}|\bar{e})\right)$. Figure 3.2 serves as a guidance for the case with Gaussian distributions. Initially, a contractor $p$ has a cost probability distribution function $c_p^0$ that is a function of his experience level $\overline{e_p}$. According to assumptions 3 and 4 and without considering any investment, a player with more experience has an initial cost distribution $c_p^0$ with both a smaller expected value as well as a smaller variance. Relying on assumption 2, the uncontrollable risk $\sigma^2$ is the same for all players while the controllable part is experience and strategy dependent. The controllable risk can be accounted for through experience which explains why a more experienced player already has a knowledge advantage that is translated into a smaller variance of the density $c_p^0$.

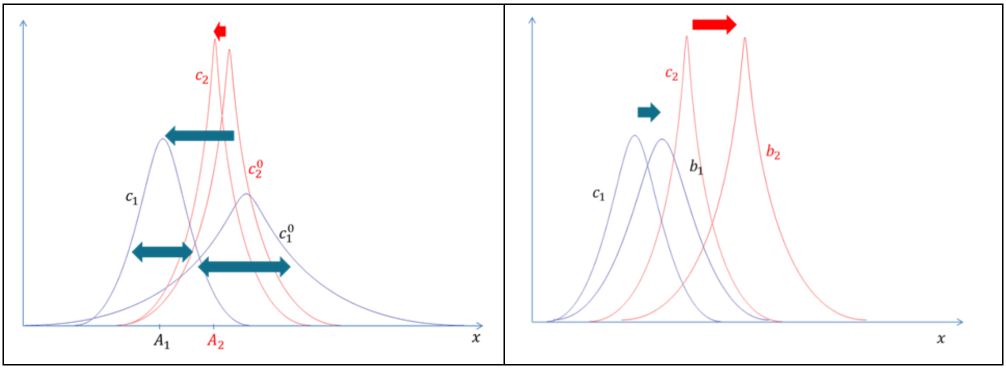


Figure 3.2 Illustration of the theoretical distributions. $c_1^0$ and $c_2^0$ are the cost probability densities for two players, where player 2 has more experience than player 1. Player 1 applies a high investment choice and player 2 made a low investment choice and arrives in $c_2$. The players apply their preferred mark-up choice (a low mark-up for player 1 and a high mark-up for player 2) arriving in the respective bidding probability densities $b_1$ and $b_2$.

Investing in research also reduces the controllable risk. For the construction of a toll road, a contractor engages in market studies in order to grasp the demand for the toll road and he may consequently align the findings with the capacity of the road. Eventually, $\sigma_p^2$ is calculated for a given investment percentage and a given experience level and is expressed as a percentage value of the initial actual cost. Besides, according to assumption 4, the investment effort also results in a leftward shift of the cost probability density. The resulting cost probability density for player $p$ is $c_p$. The second element of the strategy is the mark-up which is applied to the cost estimate that is generated from the probability distribution $c_p$. Consequently, $b_p$ represents the bid probability density for player $p$.

Assume the vector $\bar{e} = (\overline{e_1}, \overline{e_2}, \dots, \overline{e_P})$ and the strategy profile $\bar{s} = (\overline{s_1}, \overline{s_2}, \dots, \overline{s_P})$. Given the bid probability density $b_p$ for player $p$ and the associated cumulative probability distribution $B_p$, the probability of winning the contract for player $p$ is $q_p(\bar{s}|\bar{e})$ and is calculated as:

$$q_p(\bar{s}|\bar{e}) = \int_{-\infty}^{+\infty} b_p(x_p) \left[\prod_{k=1,\, p\neq k}^{P} \left(1 - B_k(x_p)\right)\right] dx_p \tag{3.2}$$

A player's instantaneous pay-off for this particular project is dependent on the fact whether the player has won or lost the tender. When a player wins, he receives the money that he requested according to the submitted proposal and the actual project cost is subtracted, together with the investment in research. In the case of a loss, the investment in research will be partly incurred, conditional on whether or not the government reimburses a fraction $d \in [0,1]$ of the research cost. It is assumed that each player wants to optimize his total expected pay-off (assumption 7). In the case of a pipeline, this total expected pay-off consists of multiple instantaneous expected pay-off values. The instantaneous expected pay-off $\rho_p$ for player $p$, is given by equation (3.3).

$$\rho_p(\bar{s}|\bar{e}) = q_p(\bar{s}|\bar{e})\left(E\left[\widetilde{B_p}\middle|\text{player } p \text{ has won}\right] - A_p\left(\overline{s_p}\middle|\overline{e_p}\right) - i\left(\overline{s_p}\right)\mu\right) - \left(1 - q_p(\bar{s}|\bar{e})\right)(1-d)\,i(\overline{s_p})\mu \tag{3.3}$$

The instantaneous expected pay-off function consists of the following building blocks:

- $\overline{s_p}$ or the strategy for a player $p$ which is associated with an investment choice $i(\overline{s_p})$ and a mark-up choice $m(\overline{s_p})$;

- $q_p(\bar{s}|\bar{e})$ or the probability that player $p$ wins the tender with $\bar{s}$ the vector of strategies $(\overline{s_1}, \overline{s_2}, \dots, \overline{s_P})$ and $\bar{e}$ the vector of experience levels $(\overline{e_1}, \overline{e_2}, \dots, \overline{e_P})$ (equation (3.2));

- $A_p(\overline{s_p}|\overline{e_p})$ or the actual cost, taking into account that player $p$ has won. It equals the expected value of the cost probability density $c_p$ that belongs to the winning contractor $p$. If $g: \mathbb{R}^2 \to \mathbb{R}$ is the function that reflects the fractional direct cost impact (assumption 4) that results from player $p$'s experience level $\overline{e_p}$ and the investment percentage $i(\overline{s_p})$ related to strategy $\overline{s_p}$, then we have $A_p = \mu\left(1 + g\left(\overline{s_p}, \overline{e_p}\right)\right)$;

- $d$ is the fraction of the investment cost that is reimbursed by the government to each losing bidder;

- $\mu$ is a scaling factor that is equal to the *a priori* expected actual cost and that is common for all bidders;

- the term $E\left[\widetilde{B_p}\middle|\text{player } p \text{ has won}\right]$ refers to the expected proposal that is made by player $p$ on the condition that he has won the tender with $\widetilde{B_p}$ a random variable from the bidding probability distribution $b_p$.

The latter building block is calculated as a conditional expectation as we know that a bidder has won the tender (according to assumption 5). Therefore, that gives analytically:

$$E\left[\widetilde{B_p} \middle| \widetilde{B_p} < \widetilde{B_k},\, \forall k \neq p\right] = \int_{-\infty}^{+\infty} x_p \frac{b_p(x_p) \prod_{k=1,p\neq k}^{P} \left(1 - B_k(x_p)\right)}{q_p(\bar{s}|\bar{e})} dx_p \tag{3.4}$$

This is obtained in line with the general idea behind the conditional expectation of a random variable $X$ given an event $Y$, or $E[X|Y] = \int_{-\infty}^{+\infty} x \frac{f_{XY}(x,y)}{f_Y(y)} dx$.

In the single-project environment of Chapter 4, the players simultaneously optimize equation (3.3). In the multi-project setting, an expected valuation of future projects needs to be added to the instantaneous pay-off. The aforementioned analysis made abstraction of the presumed distributions, while Section 3.5 discusses the actual implementation of the setting in this dissertation.

## 3.5 Implementation

In order to gain insights into the bidding dynamics, the assumptions of Section 3.2 are translated into sound analytical formulas that rely on a parametrization that leaves room for a thorough sensitivity analysis. As stated earlier, the general risk structure of the project under study is the same for all the players in the pipeline. That means that, without considering experience and pre-tender investment, the *a priori* cost probability density and its parameters are equivalent for each state of the game and for each player in the game. The experience and the current investment level may change the shape of the cost probability distribution. All models of the research project deal with Gaussian distributions that are defined by a mean value and a variance. The inputs to calculate the probability distributions consist of the (intermediate) experience vector $\bar{e} = (\overline{e_1}, \overline{e_2}, \dots, \overline{e_P})$ and the (state-specific) strategy profile $\bar{s} = (\overline{s_1}, \overline{s_2}, \dots, \overline{s_P})$. Recall that the strategy $\overline{s_p}$ consists of the investment and mark-up choices for the project under study. These are expressed as percentages: $i(\overline{s_p})\%$ for the investment and $m(\overline{s_p})\%$ for the mark-up. The exact implementation of the distributions is slightly different between the simulation approach of Chapter 4 and Chapter 5 on the one hand and the exact expected pay-off approach of Chapter 6 on the other hand, but the general rationale is the same.

In line with the reasoning of dealing with the total variance as the sum of the partial variances (i.e., omitting the covariance) and with the philosophy of diminishing scale effects, the knowledge impact assumption (assumption 3) that relates to the variance of the contractor's distributions is implemented as follows:

$$\sigma_p^2 = \sigma_p^2\left(\overline{e_p}, i\left(\overline{s_p}\right)\right) = \mu^2\left(\sigma^2 + \left(\gamma_i e^{-\lambda_i\left(100 i\left(\overline{s_p}\right)\right)}\right)^2 + \left(\gamma_e e^{-\lambda_e \overline{e_p}}\right)^2\right) \tag{3.5}$$

This formula introduces the risk parameters or the project complexity parameters. Initially, the variance has a maximum value, but investment and experience reduce the variance of the model. $\gamma_i$ is the maximum impact of a lack of project-specific investment. The larger this parameter, the greater the importance of investment on the accuracy of the cost estimate. This parameter is the key variable to model a low-risk or high-risk project. Social housing projects or sports infrastructure projects are traditionally seen as low-risk projects that have a rather predictive nature, so with a low $\gamma_i$. This is in contrast to toll roads or hospital projects that are much more risky due to the substantial demand risk or the significant number of stakeholders, resulting in a high $\gamma_i$. Equivalently, $\gamma_e$ is the maximum variance contribution of a lack of experience and quantifies the knowledge advantage of being experienced. It represents the degree of repeatability. $\lambda_i$ and $\lambda_e$ are the respective associated rate parameters that reflect the pace at which an increase of investment and experience lead to a smaller variance. Finally, $\sigma$ refers to the uncontrollable project risk or the risk share that cannot be accounted for and $\mu$ is a scaling parameter. The implementation of the direct cost impact assumption or the cost adjustment equivalently relies on diminishing scale effects and is given by:

$$g_p = g_p\left(e_p, i\left(\overline{s_p}\right)\right) = \beta_i e^{-\mu_i\left(100 i\left(\overline{s_p}\right)\right)} + \beta_e e^{-\mu_e \overline{e_p}} \tag{3.6}$$

with $\beta_i$ the innovation parameter related to the investment efforts and $\beta_e$ the efficiency parameter related to the experience. The value of $g_p$ is a fraction that acts as a cost increase to represent the inefficiency of the players and we claim that the actual cost of performing the project equals $(1 + g_p)\mu$. Without investment and without any experience, $g_p$ obtains the maximum value. Investment can reduce the cost disadvantage because of the adoption of cost decreasing innovations. Besides, experience may result in a cost benefit because of efficiency gains and scale effects. Referring to the alternative interpretation of assumption 4 (i.e., the cost adjustment), an increase in both parameters could also be interpreted as a government that favours experience and investment or quality more than purely the requested price and then expresses the monetary bid price adjustment for experience and quality.

As an example, assume that $e_u = 5$, which means that there are five experience intervals on the [0,10] scale and assume that $\sigma = 0.05$, $\gamma_i = \gamma_e = \beta_i = \beta_e = 0.1$, $\lambda_e = \mu_e = \lambda_i = \mu_i = 0.25$ and scaling parameter $\mu = € \, 1{,}000{,}000$. A player without experience ($e_1 = 0$) and a 1% investment choice thus obtains $g_p$ equal to 0.17789 and $\sigma_p$ equal to € 136,255 and for a player with experience level 4 and a 2% investment choice, we get $g_p$ equal to 0.08679 and $\sigma_p$ equal to € 86,787.

## 3.6 Overview

Before digging into the various models, an overview of the different modelling characteristics is given in Table 3.1. The table could serve as a guide for the subsequent chapters.

| | Chapter 4 | Chapter 5 | Chapter 6 |
|---|---|---|---|
| Model setting | Single-project | Multi-project with overlapping tenders | Multi-project with strictly sequential tenders |
| Subject of study | Assessment of the impact of the number of bidders, the project complexity and the government reimbursement policy on the bidding equilibrium | Assessment of the impact of a project pipeline (with and without investment spillover effects) on the findings of Chapter 4 | Assessment of the impact of a project pipeline (without investment spillover effects) on the findings of Chapter 4 |
| Decision variables for each player in subgame *e* | One investment and one mark-up percentage | Investment and mark-up percentage for each project in the pipeline (*stage*) | Investment and mark-up for each *state* that could occur in the pipeline |
| Number of strategies | Discrete investment and mark-up levels | Discrete investment and mark-up levels | Continuous investment and mark-up scale |
| Expected pay-off determination method | Simulation | Simulation | Exact for Gaussian cost probability densities |
| Model assumptions taken in this chapter (Section 3.2) | Assumptions 1 to 7 | Assumptions 1 to 10 | Assumptions 1 to 10 |
| Solution concept | Bayesian Nash equilibrium | Bayesian Nash equilibrium | Markov perfect equilibrium |
| Equilibrium approximation algorithm | Nash equilibrium method (complete enumeration) + strategy game algorithm (a best response based algorithm) | Strategy game algorithm (a best response based algorithm) | Best response algorithm |

Table 3.1 Overview of the model characteristics

# Chapter 4 Single-project environment

## 4.1 Introduction

This chapter offers a theoretical approach in order to determine the bidding equilibrium of our proposed tender model. We are mainly interested in how the bidding equilibrium changes with respect to the model parameters:

- What is the impact of the number of players and their respective experience levels on the bidding equilibrium?
- What is the impact of introducing more uncertainty in the model?
- What is the impact of a government compensation on the bidding equilibrium?

This chapter only considers a single-project environment. This means that the government has solely communicated the current project and that future opportunities are uncertain. Nevertheless, each bidder is still characterized by an experience level that reflects the qualitative aspects of his competitive position: the familiarity with the project type, the familiarity with the market, the geographic location or the financial strength of the consortium.

The contribution of this chapter to the academic literature is two-fold. On the one hand, we contribute to the academic PPP literature by building an abstract auction model that rationally addresses the pre-tender investment and mark-up questions. More particularly, the dynamic impact of project complexity and the competitive market environment on the bidding behavior are underlined and we assess the effectiveness of common governmental policies like the reimbursement of bidding costs. On the other hand, this study contributes to the auction theory by delivering an innovative procurement environment and the algorithmic, game-theoretical simulation approach succeeds in combining diverse stretches of auction and procurement research. We study the strategic behavior within a context with costly bid preparation and uncertainty in the project outcome. Moreover, we include the option of incentive creation.

Last but not least, this chapter has an important managerial contribution. Firstly, it endeavors to investigate in what sense the complexity of a project reveals the experiential discrepancies of contractors. Secondly, it gives guidance in the unsolved discussion among public institutions about how many bidders to invite. It shows that although a three-player setting for a low-risk project guarantees cheaper procurement than a two-player setting, a three-player situation might become unsustainable for a high-risk project. Thirdly, albeit partly acknowledged by practitioners, the single-project setting provides a theoretical argument that a government reimbursement of the bidding cost might relief a fraction of these first two issues.

The theoretical results of this chapter are taken further to a discussion in Section 7.2 in which the theoretical findings are triangulated with views from practitioners in the field, in order to derive founded implementable policy guidelines.

## 4.2 Literature review

### 4.2.1 The position within the PPP literature

Based on the review in Chapter 2 and the reviews of Al-Sharif and Kaka (2004), Ke et al. (2009), Tang et al. (2010) and De Clerck et al. (2012), PPPs have gained increasing attention within the academic construction literature. Concerning the procurement process itself, the focus has mainly been on the risk identification and its allocation between the government and the contractor. This is proven by the number of empirical (e.g., Li et al. 2005, Jin 2010, Chan et al. 2011) and, to a lesser extent, theoretical studies (e.g., Medda 2007, Scandizzo and Ventura 2010, Khazaeni et al. 2012, Carbonara et al. 2014[a]) that have appeared in the PPP and the concession literature. Bidding models that focus on the PPP competitive dialogue are scarce and the operations research literature has not yet explicitly studied this procurement format.

From a theoretical stretch, mainly pricing peculiarities of PPPs have been considered:

- The pricing of governmental support interventions to guarantee a minimum revenue in the course of the operation (e.g., Cheah and Liu 2006, Brandao and Saraiva 2008, Liu et al. 2014);
- The impact of governmental capacity regulations (Subprasom and Chen, 2006);
- The determination of the concession period (e.g., Ng et al. 2007, Shen et al. 2007, Zhang 2009);
- A multi-interest analysis of the financial, the social and the corporate stakes (Liou et al. 2011).

These studies do not explicitly take the competition aspect into account. This is in contrast to Iyer and Sagheer (2012) who consider the bid winning potential of a mark-up and Xu et al. (2012) who have built a system dynamics model based on past experiences for pricing the concession. The bidding model presented in this dissertation makes abstraction of the elements that determine the final price and represents the mark-up as a single figure for the consortium as a whole. On the other hand, the added complexity lies in the introduction of a competitive environment and the bidding costs for mitigating project contingencies. An attempt to combine the risk a winner faces and the current competitive mark-up determination in a non-PPP context was performed by Chao and Liou (2007) and Islam and Mohamed (2009). The PPP model additionally takes the investment option into account that reduces the long-term project risk and results in a higher quality bid.

Empirically, it is acknowledged that bidding for PPPs is expensive (Carrillo et al. 2008, Chen and Doloi 2008, De Schepper et al. 2015). Moreover, the government as a buyer prefers quality suppliers and aims to limit uncertainty (Riedl et al. 2013). The possible renegotiation of the contract can come along with high transaction costs, which might be avoided by creating proper incentives in the contract design (Bajari and Tadelis 2001). Ho (2008) questions game-theoretically whether the quality of bidding would increase if the government reimburses the second-best bidder for the bidding costs. Ho (2008) argues against the reimbursement but considers homogeneous bidders, which deviates from empirical findings of Oo et al. (2010). In a later study, Ho and Hsu (2014) allow for a heterogeneous bidding environment. The authors introduce two types of bidders: strong and regular bidders. In line with Ho (2008), a bidder can choose among two levels of investment effort: an average investment or a high investment for which the latter comes with an additional cost. In this setting, the authors do conclude that government reimbursements may be beneficial in heterogeneous environments with more than two bidders. Nonetheless, Ho and Hsu (2014) disregard contingencies, because they only attribute a specific deterministic profit to the winner. Our model not only introduces heterogeneity among contractors and allows for multiple experience levels and multiple investment levels, but it also adheres to the uncertainty of the project outcome.

### 4.2.2 Position within the auction theory literature

Even though PPP procurement has not received particular attention within the operations research literature, this study is highly intertwined with auction theory and the competitive bidding literature that was initiated by Friedman (1956). In a first instance, this particular bidding setting introduces uncertainty in the cost estimates, which originates from the studies by Curtis and Maines (1973) and Naert and Weverbergh (1978). These models only consider the mark-up decisions, while the PPP model of this dissertation also examines a pre-tender investment choice as described in Chapter 3.

Another related stream of research within the auction theory field studies a format in which investments lead to distributional upgrades of the cost distributions. Tan (1992) is the initiator considering ex-ante symmetric firms. Persico (2000), Bergemann and Välimäki (2002) and Shi (2012) studied the optimal auction design with endogenous information acquisition. These studies deviate from our setting that they do not apply the mark-up approach and assume the *ex ante* symmetric nature of bidders while more recent auction studies consider the heterogeneity among bid proposals and bidders (e.g., Maskin and Riley 2000, Engelbrecht-Wiggans et al. 2007, Skitmore 2008, Kostamis et al. 2009, Lorentziadis 2012). Moreover, the investment decision in the PPP model does not necessarily lead to a distributional upgrade, because an investment could also mean that the bidder realizes the project is more expensive than initially anticipated.

Subsequently, the heterogeneity might lead to the introduction of subsidies for investments towards inefficient bidders (i.e., bidders with a cost disadvantage) in procurement auctions. Arozamena and Cantillon (2002) study the investments for cost reductions and conclude that incentives actually have an inhibiting effect on investment due to the expectation of fiercer competition. The PPP model of this chapter acknowledges that compensations may result in fiercer competition, but this does not necessarily mean that players reduce their investment efforts. Rothkopf et al. (2003) are more in favor of subsidies and show that it lowers the expected procurement cost, while the PPP model requires some necessary differentiations and recognizes that incentives may raise the governmental expenditures.

An equivalent investment question is raised in the R&D literature in which investment does not necessarily lead to winning the contract (e.g., Canbolat et al. 2012). A similar type of incentive creation in the R&D procurement literature is studied by Zhang et al. (2013) who elaborate on the competitive investment equilibrium. Through a sharing rate of the investment between the contractor and the principal, investment incentives are created. In the PPP model, the compensation is introduced in the market for fairness purposes and is not only attributed to a specific inefficient bidder or minority, but every ex-post losing bidder possibly gets compensated.

In conclusion, to the best of our knowledge there is no theoretical research that combines pre-tender investment, cost uncertainty and incentive creation within a single auction framework. In order to be able to analytically characterize the equilibrium, traditional auction theory often assumes homogeneous bidders and studies symmetric equilibria. The PPP experiment does not take these simplifications into account which trades off against the manageability of the analytical model so that sub-optimal approximation methods are required.

## 4.3 Methodology

This chapter follows the model description, assumptions and decision variables that are discussed in Chapter 3 and looks at the single-project model.

### 4.3.1 Analytical philosophy

A strategy $s_p$ for player $p \in \{1,2,\dots,P\}$ in a particular subgame that is given by the experience vector $e = (e_1, e_2, \dots, e_P)$ is two-dimensional and consists of an investment choice $i(s_p)$ or the willingness to engage in pre-tender research and a mark-up choice $m(s_p)$ that is applied to the estimated project cost and that typically accounts for the risk premium and the profit requirement. The experience level is a particular value on the experience scale that ranges from 0 (i.e., no experience) to 10 (i.e., maximum experience) and $e_u$ the number of intervals on this scale.

Equation (3.3) calculates player $p$'s expected instantaneous pay-off $\rho_p(\bar{s}|\bar{e})$ for the project under study for a given experience vector $\bar{e}$ and strategy profile $\bar{s}$. The translation of this general setting into the single-project setting is obvious and we can consider $\bar{e} = (\overline{e_1}, \overline{e_2}, \dots, \overline{e_P}) = (e_1, e_2, \dots, e_P) = e$ and $\bar{s} = (\overline{s_1}, \overline{s_2}, \dots, \overline{s_P}) = (s_1, s_2, \dots, s_P) = s$. Moreover, since there is only a single project, we can say that the total expected pay-off $\pi_p(s|e)$ equals the instantaneous pay-off in this setting:

$$\pi_p(s|e) = \rho_p(s|e) \tag{4.1}$$

The contractors simultaneously optimize their expected pay-off so that a system of $2P$ equations needs to be solved which consists of the partial derivatives for each player's pay-off with respect to both his investment level as well as his mark-up level:

$$\begin{cases} \partial\pi_p(s^*|e) \big/ \partial i(s_p^*) = 0 \\ \partial\pi_p(s^*|e) \big/ \partial m(s_p^*) = 0 \end{cases} \qquad \forall p \in \{1,2,\dots,P\} \tag{4.2}$$

As claimed in Section 3.3, the model is a bi-level programming model and the competition among the contractors occurs at the lower level. At the upper level, the government is responsible for setting the bidding context. The government might for instance prefer to set a compensation level that minimizes the total expected payment, which would be translated into the objective function:

$$min_d \sum_{p=1}^{P} q_p(s|e) \left( E\left[\widetilde{B_p} \middle| \widetilde{B_p} < \widetilde{B_k}, \forall k \neq p\right] + \sum_{k=1,k\neq p}^{P} di(s_k)\mu \right) \tag{4.3}$$

Other governmental policies that have an influence on the lower level equilibrium are the determination of the number of players allowed to send a proposal or the cost/quality objective of the government and the number of projects in the pipeline. The qualitative objectives are hard to translate into monetary terms and we opt to list advantages and disadvantages of the policy mechanisms, so that a qualitative assessment is still required.

Albeit feasible, it is computationally intensive to calculate the expected pay-off of a strategy profile. Therefore, Section 4.3.2 elaborates on a simulation model that translates the analytical background into a simulation environment. Besides, analytically solving the system of differential equations to find a Bayesian Nash equilibrium is acknowledged to be a hard problem, which is proven by the complexity studies of Conitzer and Sandholm (2003) and Daskalakis et al. (2006). The heuristic approaches of Section 4.3.3 approximate the equilibrium.

### 4.3.2 Simulation

With the aim of attaining analytical results, stringent assumptions simplify the often complex bidding contexts. A relaxation of these assumptions makes the analysis very hard. King and Mercer (1988) acknowledge this issue in their review paper and claim that probabilistic strategies are hard to study. Simulations highly contribute to the study of a complex environment and simultaneously allow for flexibility, which also benefits managerial decision makers. Mehlenbacher (2007) shows the increasing interest of multi-agent technology to study interactions among agents and strategies in complex environments. Recent applications of numerical simulations have proven to gain insights into complex auction and procurement formats (Cai and Wurman 2005, Farnia et al. 2013, Takano et al. 2014).

A simulation experiment is the favored methodology for the study of the dynamics of a contractor's bidding behavior. Firstly, the simulation of bids avoids the computationally intensive analytical calculations. Secondly, the Monte Carlo simulations go beyond the expected value of the pay-offs, but also give insight into its distribution. Thirdly, although no closed-form expressions are possible, the simulation approach allows for considerable flexibility as different distributions can be easily tested.

Recall that the knowledge impact assumption and the cost impact assumption are given by equations (3.5) and (3.6) respectively. For the commonly known experience vector $e$, each player determines his strategy $s_p$ which refers to an investment percentage $i(s_p)$% and a mark-up percentage $m(s_p)$%. The strategy profile $s$ is then the combination of the strategies of all $P$ players and given by a vector $(s_1, s_2, \ldots, s_P)$. These elements are the inputs for the simulation of the final pay-offs. The output of the procedure is a pay-off distribution for each player. The average pay-offs for a particular strategy profile $s = (s_1, s_2, \ldots, s_p)$ are given by the pay-off vector $f = \left(f_1(s|e), f_2(s|e), \ldots, f_P(s|e)\right)$ which we assume is then an estimation of the expected pay-off vector $\pi(s|e) = \left(\pi_1(s|e), \pi_2(s|e), \ldots, \pi_P(s|e)\right)$ with $\pi_p(s|e)$ as defined in equation (4.1).

Consider Gaussian cost and bidding probability densities. In a single iteration, an actual cost and a bid for each player are generated. The reference actual cost Ã is a random variable that is drawn from the distribution $N(\mu, \sigma_u^2)$. Parameter $\mu$ is a scaling factor and in this chapter we set $\mu =$ € $1{,}000{,}000$ and $\sigma_u^2 = (\mu\sigma)^2$. This *a priori* distribution is the same for all players. The final actual cost could be different, because it is related to the particular cost distribution of the winner of the tender. The actual project cost for a particular player $p$ results from the linear transformation $\tilde{A}_p = \tilde{A}(1 + g_p)$, which is set to the mean of the cost probability density $c_p$ for player $p$ and which is unknown to the contractor at the time of bidding. Hence, $c_p$ is a nested distribution (El Otmani and Maul 2009) of the form $c_p \sim N\left(\mu(1+g_p), (1+g_p)^2(\sigma_u^2 + \sigma_p^2)\right)$. The contractor's estimated cost $\widetilde{C_p}$ is randomly selected from $c_p$ and eventually, a contractor applies the mark-up level $m(s_p)$, resulting in the bid: $\widetilde{B_p} = (1 + m(s_p))\widetilde{C_p}$. In summary, the form of the bidding probability density $b_p$ in this procurement simulation is $b_p \sim N\left(\mu(1 + m(s_p))(1+g_p), (1+m(s_p))^2(1+g_p)^2(\sigma_u^2 + \sigma_p^2)\right)$. The minimum of these simulated bids is the winning proposal and its pay-off is determined, where the actual bid is $\tilde{A}_w$ for winner $w$. The losers' pay-offs equal the fraction of the pre-tender investments that are not reimbursed by the government. As soon as a predefined number of replications $\zeta$ has been reached, the simulation algorithm stops and a pay-off distribution for each player can be determined.

### 4.3.3 Equilibrium approximation algorithms

Another simplification of the analytical model lies in the discretization of the problem. Instead of allowing an infinite number of strategies, discrete numbers of integer investment and mark-up percentages are studied. If $I$ investment choices and $M$ mark-up choices for each player are considered, the set of strategies for a player $p$ is $S_p$ and consists of $IM$ strategies. This results in $(IM)^P$ strategy profiles, which will be referred to as $S = S_1 \times S_2 \times \ldots \times S_P$. In order to approximate the equilibrium, two algorithms have been developed.

#### *4.3.3.1 Algorithm A: Nash equilibrium algorithm*

A first heuristic calculates the pay-off distribution for each strategy profile $s \in S$. For an experience vector $e$, each combination of strategies is sent to the simulation procedure explained in Section 4.3.2. The output is an average pay-off vector $f$ and the variance of the pay-offs. Afterwards, the algorithm identifies the pure strategy Nash equilibria. In accordance with equation (3.1), the Nash equilibrium $s^* = (s_1^*, s_2^*, \ldots, s_P^*)$ satisfies $\forall p, s_p \in S_p: f_p(s_p^* | e, s_{-p}^*) \geq f_p(s_p | e, s_{-p}^*)$. Moreover, we account for the variance of the pay-off distribution, so we add an additional constraint: the two-sample t-statistic needs to prove that the expected pay-off is significantly greater than the pay-off of a differing strategy.

#### *4.3.3.2 Algorithm B: Strategy game algorithm*

The second algorithm approximates the Nash equilibrium by determining a best response for a player $p$ after first restricting the strategy space $S_{-p}$ for the competitors. Given the experience vector $e = (e_1, e_2, \ldots, e_P)$, we want to determine the best response for player $p \in \{1,2, \ldots, P\}$ with experience level $e_p$. The algorithm does a prequalification of the strategies for all the $P - 1$ competitors of player $p$. Initially, every competitor $y$ has a set of strategies $S_y$ and the heuristic reduces this set to a set of shortlisted strategies $R_y$ with $n$ elements. The prequalification is done in two stages: a homogeneous stage to grasp the project characteristics in the shortlisted strategies and a heterogeneous stage to emphasize the competition aspect. After the prequalification, the strategy game algorithm is executed. A detailed overview of the algorithms is given in Appendix B.

*Homogeneous stage*

Player $y$ with experience level $e_y$ has a set of strategies $S_y$ at his possession. The homogeneous stage resembles a knock-out tournament. A predefined number of rounds $r$ is set and the experience levels are set equal to $y$'s experience level $e_y$ for all players. In the first round, $P^r$ strategies are randomly selected and divided in $P^{r-1}$ groups of $P$ strategies. For each group of strategies, the average pay-offs are calculated and the best performing strategy continues to the next round where only $P^{r-1}$ strategies are outstanding. The procedure continues until $P$ strategies remain and these are transferred to the set of shortlisted strategies $R_y$.

*Heterogeneous stage*

In this second stage, we keep the original experience vector $e$ and for each competitor $y$, an intermediate game is played in which all his strategies are assessed against random strategies for his opponents. In every iteration of the algorithm, random strategies from the complete set of strategies are selected for the competitors of player $y$. This results in the vector $s_{-y}$ which represents the strategy profile for the opponents of player $y$. Next, the expected pay-off and its variance are calculated for all the possible strategies from the set $S_y$ given the strategy profile $s_{-y}$ for his competitors and the experience vector $e$. In the next iteration, new strategies are randomly selected for player $y$'s competitors. After a user-defined number of iterations $k_1$, the pay-off distribution for each strategy of player $y$ is derived and the best strategies are selected to be part of the shortlisted strategy list $R_y$.

*Strategy game algorithm*

After the shortlisting is performed for each competitor $y$ of player $p$, the final assessment stage starts. For each iteration of the algorithm, strategies are selected for the competitors of player $p$. For each competitor $y$, these strategies are generated from the respective shortlisted sets $R_y$, resulting in a strategy profile $s_{-p}$. Player $p$ will now calculate the pay-off for each of the strategies of his set $S_p$. In the next iteration, new strategies are selected for the opponents of player $p$ and the pay-offs for this iteration are calculated. After $k_2$ iterations, the average pay-off over all executed runs is calculated for each of the strategies from the set $S_p$ and the overall best performing strategy for player $p$ is assumed to be a good proxy for the equilibrium strategy for this player.

### 4.3.4 Experimental setting

Both algorithms have been implemented in Microsoft Visual Studio 2010. Tables 4.1-4.3 recapitulate the explanation of the parameter values that define the scenarios, the tested strategies and the algorithm specifications. For each scenario, the equilibrium strategies have been calculated and based on an ANOVA analysis, we check how the equilibrium is modified according to changes in the parameters. The output of the Nash equilibrium algorithm is the pure strategy Nash equilibrium strategy profile, while the strategy game algorithm output reports the approximate equilibrium strategy for a single player.

| Parameter | Interpretation | Values |
|---|---|---|
| $\sigma$ | Uncontrollable project risk | 0.05,0.10,0.15 |
| $\gamma_e$ | Maximum risk impact of a lack of experience | 0.05,0.10 |
| $\gamma_i$ | Maximum risk impact of a lack of investment | 0.05,0.10,0.20 |
| $\lambda_e$ | Experiential learning rate | 0.25,0.50 |
| $\lambda_i$ | Investment learning rate | 0.25,0.50 |
| $\beta_e$ | Experiential cost disadvantage | 0.05,0.10 |
| $\beta_i$ | Investment cost disadvantage | 0,0.05 |
| $\mu_e$ | Experiential cost decrease rate | 0.25,0.50 |
| $\mu_i$ | Investment cost decrease rate | 0.25,0.50 |
| $d$ | Government compensation level | 0,0.5,0.8,0.9 |

Table 4.1 Parameter values used in the strategy game model

| | Nash equilibrium game | Strategy game |
|---|---|---|
| Experience levels | 0,5,10 | 0,2,4,6,8,10 |
| Investment levels | 0%,2%,4%,…,10% | 0%,1%,2%,…,20% |
| Mark-up levels | 0%,8%,16%,…,40% | 0%,1%,2%,…,50% |
| Number of strategies | 36 | 1,071 |

Table 4.2 Values for situation factors and the possible choices for the investment percentages and the mark-up percentages

| Parameter | Interpretation | Value |
|---|---|---|
| $\mu$ | Initial mean project cost | 1,000,000 |
| $\zeta$ | Number of simulation runs for pay-off calculation | 1,000 |
| $n$ | Number of elements in strategy database $R_q$ | 10 |
| $k_1$ | Number of iterations in the strategy game method | 100 |
| $k_2$ | Number of iterations in the heterogeneous game | 1,000 |
| $r$ | Number of rounds in the homogeneous game | 6 |

Table 4.3 Used values in the experiments for the different heuristics

## 4.4 Experimental results

Two algorithms are implemented in order to study the bidding dynamics. Section 4.4.1 starts with comparing both algorithms from a computational perspective. The subsequent sections quantitatively discuss the results from the experiments.

### 4.4.1 Performance of the algorithms

The Nash equilibrium heuristic has the advantage that it considers the entire search space and calculates the average pay-offs for each strategy profile. Consequently, the computation times skyrocket when more strategies are taken into account. As the heuristic only looks into unique Nash equilibria, sometimes no equilibrium is reported within the pre-set time limit (which occurred in 32.4% of the cases if $\zeta = 1{,}000$). If multiple equilibria are found, a pay-off dominance mechanism selects the highest pay-off generating equilibrium. Equilibrium examples for the Nash equilibrium heuristic are shown in Table 4.4. The strategy game heuristic reduces computation times if the number of strategies increases, but has the disadvantage that it limits the search space, so that one might end up in a local optimum. Additionally, it only looks at a single player's best response and does not look into the *full* equilibrium. This means that the algorithm is not able to reveal the asymmetric strategy equilibrium of equally experienced players for instance.

Since both algorithms are developed for a different set of problems, it is still of a major interest to assess and compare the performance. In brief, three questions could be asked:

1) How does the strategy game algorithm perform against the full enumeration of the Nash equilibrium method with respect to the computation times?
2) What is the fraction of scenarios for which no unique equilibrium can be identified for a given number of simulation runs in the Nash equilibrium method?
3) For the scenarios in which the Nash equilibrium method defines an equilibrium within a pre-set time frame: how close is this equilibrium to the best response that is suggested by the strategy game algorithm?

In order to be able to compare the algorithms, the number of strategies needs to be reduced. This is due to the limitations of the Nash equilibrium algorithm for which a large set of strategies would result in very extensive computation times (because of the explicit enumeration) and in a greater probability that a unique equilibrium could not be identified within the specified time frame. On the other hand, the best response heuristic is developed for problems with a large set of strategies, because it works with a prequalification of strategies (so a reduction of the set of strategies for the opponents). In the original setup (Section 4.3.4), the prequalification stage selects ten out of the 1,071 strategies for the opponents. With a limited set of strategies, prequalifying a large fraction of the possible strategies could result in misleading solutions. Therefore, in a slightly adapted version of the algorithm, only three strategies are prequalified.

| | Model parameters | | | | | | | | | | Sub-game | | | Nash equilibrium Investment/mark-up (simulated pay-off) | | | Gvt. cost |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ex. | $\sigma$ | $\gamma_e$ | $\gamma_i$ | $\lambda_e$ | $\lambda_i$ | $\beta_e$ | $\beta_i$ | $\mu_e$ | $\mu_i$ | $d$ | $e_1$ | $e_2$ | $e_3$ | $s_1^*$ | $s_2^*$ | $s_3^*$ | |
| 4.4.3 Project risk (uncontrollable) | | | | | | | | | | | | | | | | | |
| 1 | 0.05 | 0.05 | 0.05 | 0.25 | 0.25 | 0.05 | 0.05 | 0.25 | 0.25 | 0 | 0 | 5 | 10 | 0%/8% (4,309) | 0%/8% (23,526) | 0%/8% (31,549) | 1,083,146 |
| 2 | 0.1 | 0.05 | 0.05 | 0.25 | 0.25 | 0.05 | 0.05 | 0.25 | 0.25 | 0 | 0 | 5 | 10 | 0%/16% (15,633) | 0%/16% (37,007) | 0%/16% (44,449) | 1,116,535 |
| 3 | 0.15 | 0.05 | 0.05 | 0.25 | 0.25 | 0.05 | 0.05 | 0.25 | 0.25 | 0 | 0 | 5 | 10 | 0%/24% (24,330) | 0%/24% (44,591) | 0%/24% (55,404) | 1,144,562 |
| 4.4.3 Project risk (controllable) | | | | | | | | | | | | | | | | | |
| 4 | 0.05 | 0.05 | 0.1 | 0.25 | 0.25 | 0.05 | 0.05 | 0.25 | 0.25 | 0 | 0 | 5 | 10 | 0%/16% (14,303) | 0%/16% (37,453) | 0%/16% (40,291) | 1,117,603 |
| 5 | 0.05 | 0.05 | 0.2 | 0.25 | 0.25 | 0.05 | 0.05 | 0.25 | 0.25 | 0 | 0 | 5 | 10 | 0%/40% (9,002) | 2%/24% (40,795) | 2%/24% (48,844) | 1,161,433 |
| 4.4.4 Government intervention | | | | | | | | | | | | | | | | | |
| 6[a] | 0.05 | 0.05 | 0.1 | 0.25 | 0.25 | 0.05 | 0.05 | 0.25 | 0.25 | 0.6 | 0 | 5 | 10 | 0%/16% (10,599) | 2%/16% (29,101) | 2%/16% (39,000) | 1,143,690 |
| 7[a,e] | 0.05 | 0.05 | 0.1 | 0.25 | 0.25 | 0.05 | 0.05 | 0.25 | 0.25 | 0.8 | 0 | 5 | 10 | 2%/16% (11,240) | 2%/16% (34,030) | 2%/16% (40,862) | 1,170,817 |
| 8[b,f] | 0.05 | 0.05 | 0.1 | 0.25 | 0.25 | 0.05 | 0.05 | 0.25 | 0.25 | 0.8 | 5 | 5 | 5 | 2%/16% (26,565) | 2%/16% (27,179) | 2%/16% (28,116) | 1,162,372 |
| 9[b] | 0.05 | 0.05 | 0.2 | 0.25 | 0.25 | 0.05 | 0.05 | 0.25 | 0.25 | 0.6 | 5 | 5 | 5 | 4%/16% (5,026) | 4%/16% (7,624) | 4%/16% (6,493) | 1,159,656 |
| 10[c] | 0.05 | 0.05 | 0.2 | 0.25 | 0.25 | 0.05 | 0.05 | 0.25 | 0.25 | 0.4 | 0 | 5 | 10 | 0%/40% (-4,407) | 4%/16% (17,071) | 4%/16% (23,158) | 1,135,921 |
| 11[c] | 0.05 | 0.05 | 0.2 | 0.25 | 0.25 | 0.05 | 0.05 | 0.25 | 0.25 | 0.8 | 0 | 5 | 10 | 4%/24% (-2,669) | 4%/16% (20,353) | 4%/16% (31,608) | 1,189,107 |
| 12[d] | 0.05 | 0 | 0.1 | 0.25 | 0.25 | 0.05 | 0.05 | 0.25 | 0.25 | 0.8 | 0 | 5 | 10 | 2%/16% (12,188) | 2%/16% (31,526) | 2%/16% (40,268) | 1,167,906 |
| 13[d] | 0.05 | 0 | 0.1 | 0.25 | 0.25 | 0.1 | 0.05 | 0.25 | 0.25 | 0.8 | 0 | 5 | 10 | 0%/16% (3,240) | 2%/16% (35,817) | 2%/16% (53,504) | 1,169,270 |
| 4.4.5 Other findings | | | | | | | | | | | | | | | | | |
| 14[d] | 0.05 | 0.05 | 0.05 | 0.25 | 0.25 | 0.1 | 0.05 | 0.25 | 0.25 | 0 | 0 | 5 | 10 | 0%/16% (1,087) | 0%/8% (29,101) | 0%/8% (50,710) | 1,107,749 |
| 15[e] | 0.05 | 0.1 | 0.1 | 0.25 | 0.25 | 0.05 | 0.05 | 0.25 | 0.25 | 0.8 | 0 | 5 | 10 | 0%/24% (3,634) | 2%/16% (33,093) | 2%/16% (54,650) | 1,152,327 |
| 16[f] | 0.05 | 0.05 | 0.1 | 0.5 | 0.5 | 0.05 | 0.05 | 0.25 | 0.25 | 0.4 | 5 | 5 | 5 | 0%/16% (4,689) | 2%/8% (10,865) | 2%/8% (11,738) | 1,087,805 |

Table 4.4 Equilibria examples from the Nash equilibrium algorithm ($\zeta = 1{,}000$)

[a] Players react differently to compensation according to experience levels
[b] Higher innovation parameter is incentive to invest sooner
[c] Compensation helps to open up the market
[d] The efficiency parameter affects investment and mark-up behavior of inexperienced players
[e] The experiential knowledge requirement affects the inexperienced player's strategy
[f] The learning rates affect the speed of the compensation effect

The comparison test focused on the three-player setting and the following parameter settings that define the scenarios:

- $\gamma_i$ with values 0.05, 0.1 and 0.2
- $\gamma_e$ with values 0.05 and 0.1
- Experience levels 0, 5 and 10
- The other parameters remain constant: $\beta_i = 0.5; \beta_e = 0.1; \lambda_i = \lambda_e = \mu_i = \mu_e = 0.25; d = 0;\ \mu = € \ 1{,}000{,}000$

Both algorithms have been executed for the case with $I$ equal to 6 (0%, 2%, …, 10%) or 11 (0%,1%,…,10%) and $M$ equal to 6 (0%,8%,…,40%) or 11 (0%,4%,…,40%). Both algorithms also rely on the number of repetitions $\zeta$ for the pay-off calculation in the simulation (Section 4.3.2). This parameter is important in order to investigate how many runs are needed in order to arrive at a distinct equilibrium in the Nash equilibrium method. If this parameter is too low, the variance of the pay-off will be too large, meaning that there might not be a significant difference in the expected pay-off of two neighboring strategies. This would result in a situation for which the Nash equilibrium method is not able to find a unique equilibrium. Table 4.5 answers questions (1) and (2) and summarizes the computation times for the two methods. The percentage of cases for which an equilibrium is found in the Nash equilibrium method is also reported (while the strategy game algorithm always reports an optimal best response).

The table shows that computation times rise sharply when more simulation runs or more strategies are involved. Moreover, the number of runs greatly impacts the fraction of scenarios for which an equilibrium is identified. It is clear that the Nash equilibrium algorithm requires a lot of simulation runs before an equilibrium can be reported for these scenarios. Of course, we need to point to the fact that it could be possible that no equilibrium in unique strategies exists for a particular scenario.

Table 4.6 studies the convergence attribute of the strategy game algorithm. The strategy game always reports a best response as a proxy for the player’s optimal bidding behavior. With the parameter values as mentioned earlier, there are 108 scenarios. For each of these, we looked at the convergence capability for 6 and 11 investment levels together with 6 or 11 mark-up levels. For the results in the paper, $\zeta$ is set to 1,000 as that number gave satisfactory convergence results. The table reports the fraction of scenarios for which the strategy change was larger than a move to a neighboring strategy. A neighboring strategy is defined as a strategy for which the investment and/or mark-up is one level higher or lower than the current level.

For the test set, high-risk scenarios (i.e., $\gamma_i = 0.2$) require more runs to obtain convergence. This is also the result of the fact that there is not a symmetric optimal strategy for players with the same experience level. In a high-risk setting with experience vector (0,0,5) for instance, one of the two inexperienced players should actually not participate. As the strategy game algorithm only reports a single best response, it will, depending on the progress of the simulation, sometimes return the no-participation strategy and in other cases a participation strategy. This is why in these cases we still need some insights from the Nash equilibrium algorithm. Therefore, it is rather daunting to compare the two methodologies. Nevertheless, as a final step, the best response output of the strategy game is compared with the equilibrium outcome of the Nash equilibrium method in this particular setting when $\zeta = 3{,}000$. As a result, 23.6% of the scenarios gave exactly the same result. If we allow the strategies to be neighboring strategies as defined earlier, 88.4% of the scenarios resulted in the same solution in both algorithms. Especially in the scenarios for which we only allowed 36 strategies (i.e., 6 investment levels and 6 mark-up levels), the strategy game often reports a mark-up that is one level higher. This can be attributed to the fact that the strategy game is mainly developed to deal with a large number of strategies. In the prequalification stage, the algorithm selects promising strategies for the opponents, but when there are only a limited number of strategies with large gaps inbetween (like mark-up gaps of 8%), this might involve that also some “bad” strategies are selected for the opponents, allowing the contractor to inflate the mark-ups.

| $I$ | $M$ | $\zeta$ | % of scenarios for which solution was found | Computation time Nash equilibrium method per scenario (sec.) | Computation time strategy game method per scenario (sec.) |
|---|---|---|---|---|---|
| 6 | 6 | 50 | 28.3% | 1.11 | 17.33 |
| 6 | 6 | 100 | 33.3% | 2.69 | 34.55 |
| 6 | 6 | 500 | 66.7% | 5.99 | 172.93 |
| 6 | 6 | 1000 | 75.0% | 13.4 | 350.46 |
| 6 | 6 | 2000 | 80.0% | 19.97 | 715.31 |
| 6 | 6 | 3000 | 76.7% | 33.53 | 1046.9 |
| 6 | 11 | 50 | 3.3% | 6.23 | 33.54 |
| 6 | 11 | 100 | 3.3% | 13.21 | 66.38 |
| 6 | 11 | 500 | 21.7% | 64.41 | 331.3 |
| 6 | 11 | 1000 | 41.7% | 133.18 | 645.51 |
| 6 | 11 | 2000 | 58.3% | 215.63 | 1305.06 |
| 6 | 11 | 3000 | 58.3% | 315.27 | 1935.34 |
| 11 | 6 | 50 | 20.0% | 5.99 | 31.83 |
| 11 | 6 | 100 | 25.0% | 10.36 | 63.71 |
| 11 | 6 | 500 | 63.3% | 55.38 | 317.98 |
| 11 | 6 | 1000 | 70.0% | 125.25 | 636.88 |
| 11 | 6 | 2000 | 88.3% | 215.53 | 1279.23 |
| 11 | 6 | 3000 | 91.7% | 351.33 | 1908.93 |
| 11 | 11 | 50 | 3.3% | 87.22 | 58.25 |
| 11 | 11 | 100 | 6.7% | 131.93 | 116.57 |
| 11 | 11 | 500 | 23.3% | 737.13 | 583.84 |
| 11 | 11 | 1000 | 31.7% | 1337.92 | 1168.01 |
| 11 | 11 | 2000 | 63.3% | 2712.81 | 2334.61 |
| 11 | 11 | 3000 | 73.3% | 4600.22 | 3429.29 |

Table 4.5 Results of the comparative study

| | $\zeta$: 50→100 | $\zeta$:100→500 | $\zeta$:500→1000 | $\zeta$:1000→2000 | $\zeta$:2000→3000 |
|---|---|---|---|---|---|
| $I = 6$ $M = 6$ | 5.6% (1.4%) | 5.6% (1.4%) | 3.7% (0.0%) | 3.7% (0.0%) | 0.9% (0.0%) |
| $I = 6$, $M = 11$ | 12.0% (6.9%) | 10.2% (6.9%) | 13.0% (6.9%) | 8.3% (4.2%) | 7.4% (0.0%) |
| $I = 11$ $M = 6$ | 11.1% (5.6%) | 4.6% (0.0%) | 3.7% (1.4%) | 2.8% (0.0%) | 0% (0.0%) |
| $I = 11$ $M = 11$ | 17.6% (8.3%) | 11.1% (8.3%) | 7.4% (4.2%) | 9.3% (2.8%) | 5.6% (2.8%) |

Table 4.6 Results of the convergence study for the strategy game algorithm. The percentages represent the fraction of scenarios for which a change larger than a move to a neighboring strategy occurs for an increase in $\zeta$. The fractions between brackets give the results of the scenarios for which $\gamma_i \neq 0.2$.

### 4.4.2 Bidding environment

The bidding environment refers to the number of competitors and their respective experience levels. Figure 4.1 and Figure 4.2 contain the output of the two sensitivity studies of a strategy game with three players and report the equilibrium response for a reference contractor with the experience level $e_1$ tabulated in the upper left corner of each matrix and the competitors' experience levels on the horizontal and vertical axes. Each strategy consists of an investment level (i.e., elements below the diagonal) and a mark-up level (i.e., elements above the diagonal). A glance at both figures confirms the significant interaction of a player's experience relative to the maturity of the two opponents. Ceteris paribus, two general dynamics are apparent:

1. The more experienced a player is, the lower will be the mark-up and the higher the investment percentage;
2. The smaller the competitive disadvantage for a given experience level compared to the level of the opponents, the lower the mark-up and the higher the investment percentage.

Even for small experience gaps, the least experienced player is not or only limitedly motivated to perform the risky upfront investment. The latter effect is more outspoken in the lower experience cases, but flattens out as soon as $e_1 \geq 4$. The interaction plot of Figure 4.3 additionally reveals that an incumbent player exploits his knowledge and cost advantage over newcomers by increasing the mark-ups.

The behavioral dynamics differ according to the experience-related parameters. In case of an increase of the cost disadvantage parameter $\beta_e$, inexperienced players loose competitiveness and respond with higher mark-up levels. This is the result of a larger shift of the cost curves that gives rise to higher winning probabilities for experienced players. If governments attribute more attention to past experience, inexperienced players will be reticent to come up with a competitive proposal, leading to a possible saturation of the market. A similar competition inhibiting effect is related to the knowledge requirement parameter $\gamma_e$ when a project's complexity necessitates more experience. The margin rockets and puts a break on the investment of inexperienced players, thus limiting competition. Consequently, attributing more attention to experience does not necessarily invoke lower government expenditures (Figure 4.4).

An important characterization of the bidding environment is the number of players. The cumulative distributions of Figure 4.5 illustrate the consequences of inviting a fourth bidder. The optimal investment response and the average pay-offs in equilibrium are clearly lower than in the three player-environment. Less experienced players are much more reluctant to invest because of the decreased probability of winning. In the four-player case, the experiment shows that players stay out of the market more often, which is proven by the increased frequency of the maximum mark-up choice from 5.1% of the responses in the three-player case to 10.7% of the responses in the four-player scenarios. At the experienced side of the spectrum though, mature bidders might decrease their mark-ups because of the increased competition. According to the experiment, government incentives are less effective in a four-player setting, especially for the incentive creation of inexperienced players.

Two-player results look more promising from a competition perspective (Figure 4.6): there is a more levelled behavior of the players. Inexperienced players tend to be aware of their reasonable probability of winning and the combination of competitive forces and the avoidance of the winner's curse actually keeps them in the market. Nevertheless, the mark-ups soar, so that a higher government cost might be expected.

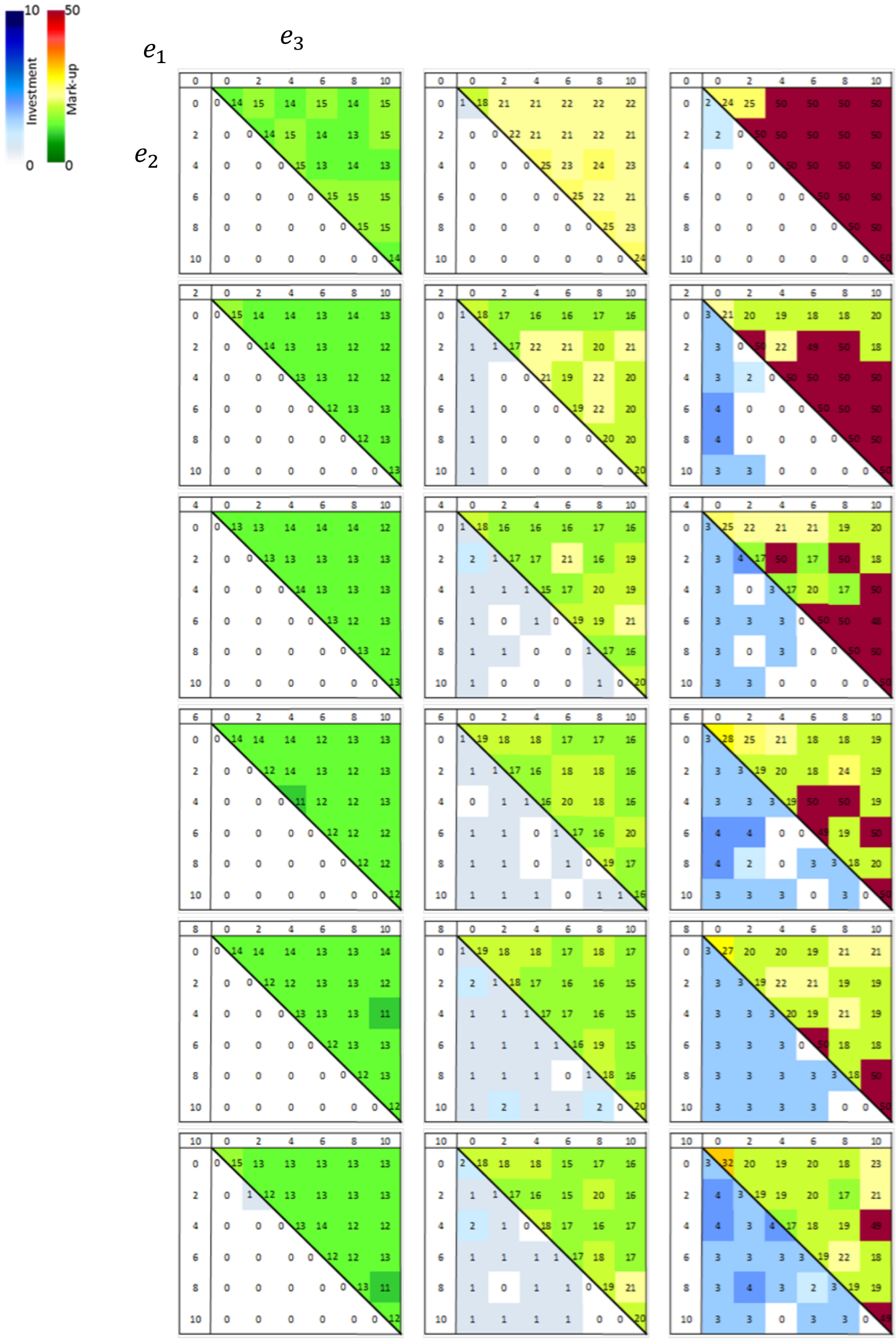


Figure 4.1 Impact of the controllable uncertainty on the bidding behavior in a 3-player game ($\lambda_1 = \lambda_2 = \mu_1 = \mu_2 = 0.25$, $\gamma_e = \beta_e = \beta_i = 0.05$, $\sigma = 0.05$, $d = 0$) with innovation parameter $\gamma_i$ (from left to right) 0.05, 0.1 and 0.2

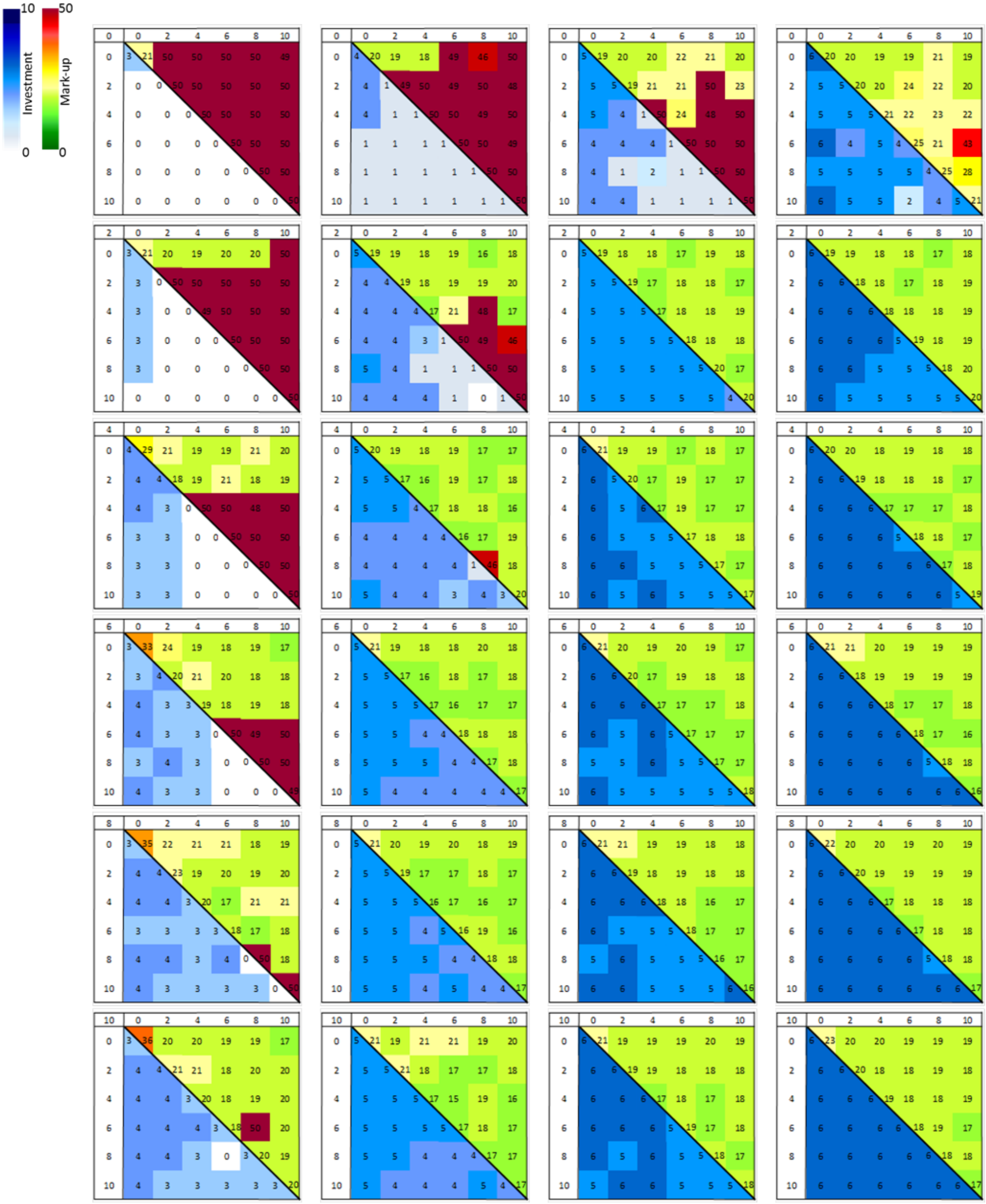

Figure 4.2 Impact of the compensation on the bidding behavior in a 3-player game ($\lambda_1 = \lambda_2 = \mu_1 = \mu_2$ = 0.25, $\gamma_e$ = 0.05, $\gamma_i$ = 0.20, $\beta_e$ = 0.10, $\beta_i$ = 0.05, $\sigma$ = 0.05) with government compensation level $d$ (from left to right) 0%, 50%, 80% and 90%

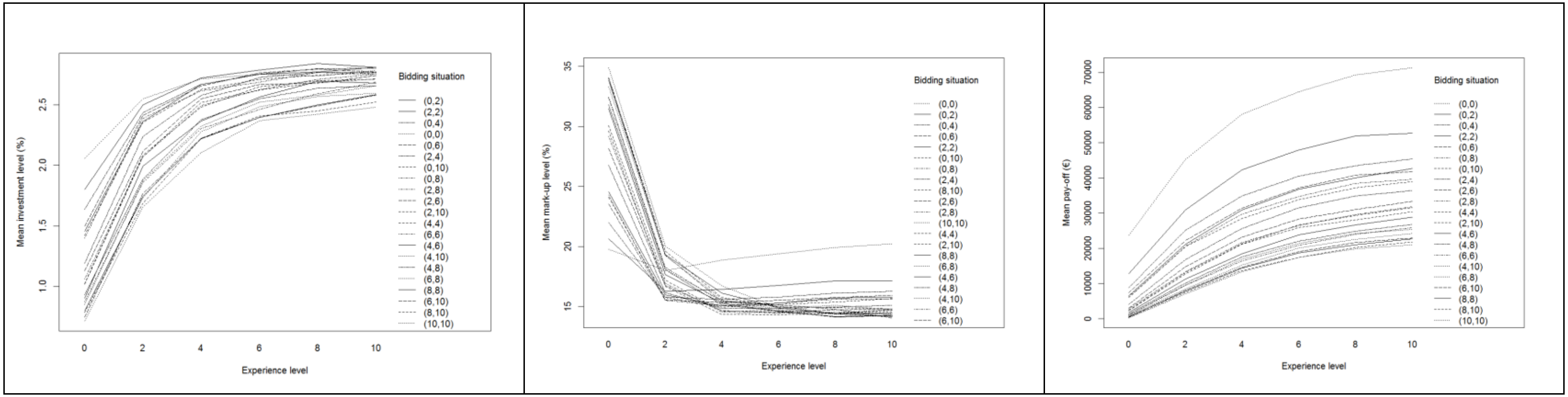


Figure 4.3 [strategy game algorithm] The interaction between $e_1$ and the bidding situation $(e_2, e_3)$ in relationship with the investment level, the mark-up level and the pay-off for the scenarios in which $\sigma$=5%

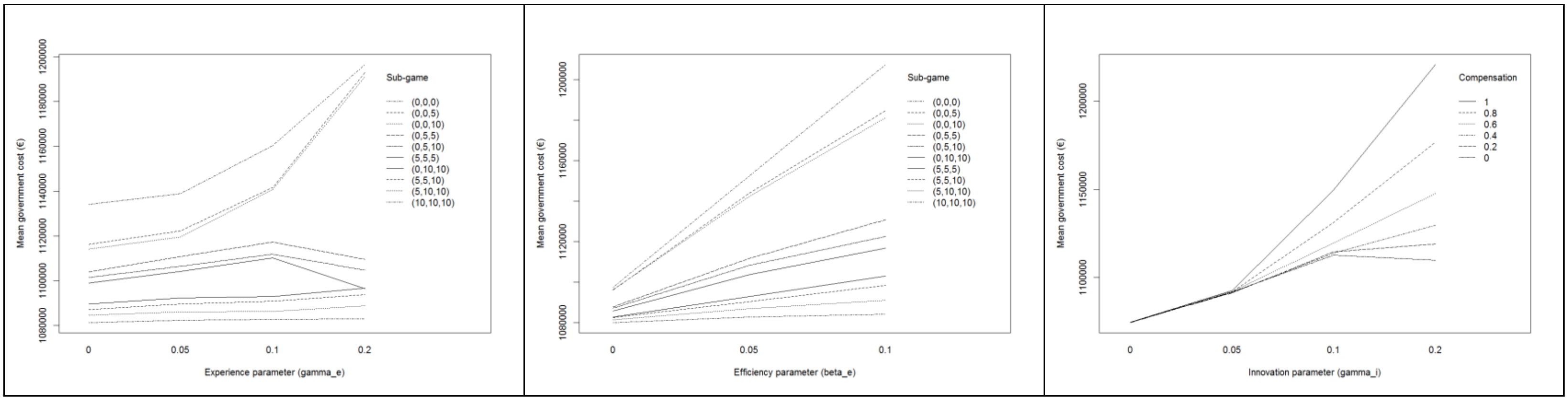


Figure 4.4 [Nash equilibrium algorithm] Interaction plots of the model parameters with respect to the government procurement cost for all the scenarios with $\sigma$ = 5%

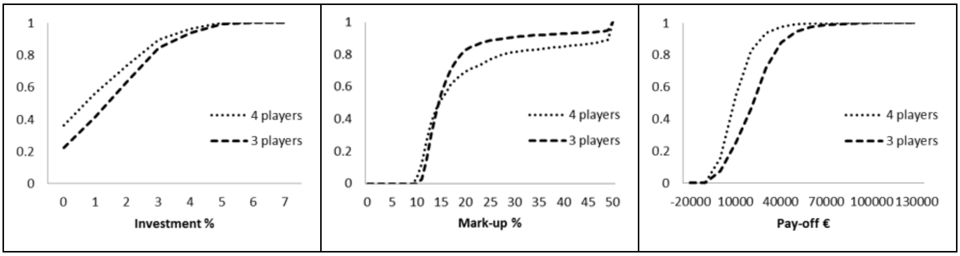


Figure 4.5 [strategy game algorithm] Cumulative distribution of the aggregated scenario outcomes for $\sigma$ = 5%

$e_2$ (columns), $e_1$ (rows)

| MU | 0 | 2 | 4 | 6 | 8 | 10 |
|---|---|---|---|---|---|---|
| 0 | 19 | 18 | 17 | 17 | 17 | 18 |
| 2 | 20 | 18 | 18 | 16 | 17 | 18 |
| 4 | 21 | 19 | 18 | 18 | 18 | 16 |
| 6 | 21 | 19 | 19 | 18 | 18 | 18 |
| 8 | 20 | 19 | 19 | 17 | 18 | 18 |
| 10 | 20 | 19 | 18 | 17 | 18 | 18 |

| MU | 0 | 2 | 4 | 6 | 8 | 10 |
|---|---|---|---|---|---|---|
| 0 | 22 | 19 | 19 | 18 | 18 | 19 |
| 2 | 23 | 20 | 19 | 19 | 19 | 19 |
| 4 | 22 | 20 | 20 | 18 | 20 | 18 |
| 6 | 20 | 20 | 22 | 20 | 18 | 18 |
| 8 | 22 | 20 | 20 | 20 | 20 | 20 |
| 10 | 23 | 21 | 19 | 19 | 20 | 20 |

| MU | 0 | 2 | 4 | 6 | 8 | 10 |
|---|---|---|---|---|---|---|
| 0 | 23 | 22 | 21 | 22 | 21 | 22 |
| 2 | 24 | 23 | 20 | 21 | 22 | 21 |
| 4 | 25 | 21 | 21 | 20 | 21 | 21 |
| 6 | 26 | 22 | 20 | 20 | 21 | 20 |
| 8 | 25 | 22 | 23 | 21 | 23 | 21 |
| 10 | 25 | 23 | 22 | 21 | 21 | 22 |

| INV | 0 | 2 | 4 | 6 | 8 | 10 |
|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 1 | 0 | 1 | 1 |
| 4 | 0 | 1 | 0 | 1 | 1 | 0 |
| 6 | 1 | 0 | 1 | 1 | 1 | 1 |
| 8 | 1 | 1 | 1 | 1 | 0 | 1 |
| 10 | 1 | 1 | 1 | 1 | 1 | 1 |

| INV | 0 | 2 | 4 | 6 | 8 | 10 |
|---|---|---|---|---|---|---|
| 0 | 2 | 2 | 2 | 2 | 2 | 2 |
| 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 4 | 2 | 2 | 2 | 2 | 2 | 2 |
| 6 | 2 | 2 | 2 | 2 | 2 | 2 |
| 8 | 2 | 2 | 2 | 2 | 2 | 2 |
| 10 | 2 | 2 | 2 | 2 | 2 | 2 |

| INV | 0 | 2 | 4 | 6 | 8 | 10 |
|---|---|---|---|---|---|---|
| 0 | 4 | 4 | 4 | 4 | 4 | 4 |
| 2 | 4 | 4 | 4 | 4 | 4 | 4 |
| 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| 6 | 4 | 4 | 4 | 4 | 4 | 4 |
| 8 | 4 | 4 | 4 | 4 | 4 | 4 |
| 10 | 4 | 4 | 4 | 4 | 4 | 4 |

Figure 4.6 Impact of the controllable uncertainty on the bidding behavior in a 2-player setting with the optimal mark-up in the upper panes and optimal investment in the lower pane ($\lambda_1 = \lambda_2 = \mu_1 = \mu_2$ = 0.25, $\gamma_e$ = 0.05, $\beta_e$ = 0.05, $\beta_i$ = 0.05, $\sigma$ = 0.05, $d$ = 0) and with $\gamma_i$ (from left to right) 0.05, 0.1 and 0.2

### 4.4.3 Project characteristics

The model accounts for complexity and (controllable and uncontrollable) uncertainty in the form of the variance of the contractor's cost probability density. Concerning the controllable risk share, the influence of the innovation parameter $\gamma_i$ deserves particular attention. $\gamma_i$ is project-specific and the associated variability can be accounted for by performing pre-tender research (e.g., surveys, feasibility studies, R&D) and is not reduced by past project experience. $\gamma_i$ attains relatively higher values for highly complex transportation projects than for social housing projects. The parameter has a mark-up impact and an investment impact regardless of the experience level (Figure 4.7), but the scale of the impact differs conditioning on the experience level (Figure 4.1). Experienced players move towards a high mark-up together with a higher investment if $\gamma_i$ increases. Inexperienced players ($e_1 = 0$) with a competitive disadvantage move towards the cap mark-up value of 50% without investment which means that they do not participate. This is accelerated when also the experiential cost disadvantage parameter $\beta_e$ or the uncertainty due to a lack of experience $\gamma_e$ increases. In fact, this implies that inviting three bidders to bid on a project is unsustainable in subgames with less experienced players. Government incentive creation mechanisms could especially be interesting in these scenarios.

The uncontrollable risk is related to force majeure risk, permits risk or an unaccountable part of the demand risk for instance and has an exponential impact on the preferred mark-up. The uncontrollable project risk is an inhibitor for investment behavior. The players safeguard against the downside risk of exuberant costs, resulting in larger government expenditures and contractors' pay-offs (Figure 4.7). Interestingly, as the share of the uncontrollable project risk gets larger, ceteris paribus, the heterogeneity among players and the disadvantage of the inexperienced player is dissolving and the players' behavior converges. As it comes at a large expense, the public entity should beware of transferring uncontrollable risk. Albeit a different setting, this finding is related to the linkage principle of Milgrom and Weber (1982[b]) and studied in an asymmetric context by Campbell and Levin (2000) and Quint (2010). These authors claim that sharing publicly available information results in a homogeneous market and more competition, which subsequently leads to a larger value for the seller. In our context, transferring uncontrollable risk results in a more homogeneous market but also involves more uncertainty, leading to an increase in the government procurement cost.

### 4.4.4 Government reimbursement

In Chapter 3, we have introduced a percentage-wise compensation $d$ to all the losing bidders. In line with the expectations, a surge in the government compensation level leads to a significant increase in the average investment level, but the effect's magnitude and the threshold $d$ that shifts the equilibrium interacts with other parameters that define whether and when a reimbursement is justified. As shown in the three-player setting of Figure 4.2, a less experienced player demands a higher compensation contribution. Moreover, the movement towards an investment initially manifests itself in situations where the competitor has a competitive strength, i.e., a subgame in which at least one opponent has an experience level that does not surpass that of the contractor. The threshold compensation level that makes the equilibrium shift towards higher investment levels is inversely related to the innovation parameter $\gamma_i$. In the complex and high-risk scenarios ($\gamma_i$=0.2), the introduction of a reimbursement beyond the threshold levels the playing field and prevents players from staying out of the market. Figure 4.2 suggests that a compensation of 50% of the investment cost can convince players with experience level $e_1 = 4$ to actively participate, regardless of the competitive position of its opponents. According to the algorithm output, compensations of 80% trigger participation for players with $e_1 = 2$ regardless of the competition and $e_1 = 0$ if the knowledge gap is within bounds. According to Figure 4.2 and the interaction plots of Figure 4.7 and Figure 4.8, there is an overall investment jump and a large drop in the mark-up. In the case with a small controllable uncertainty, there is a lesser need to attribute compensations, but they may stimulate innovation and research to prevent renegotiation issues. In that case, the compensation levels should be even higher (i.e., 90%) compared to high-risk projects, which comes at a considerable cost. From a practical point of view though, the government may only install a single compensation policy and it is not allowed to favor particular players over others, which is in contrast to the study of Rothkopf et al. (2003) that offers incentives to the inefficient bidders.

As a conclusion, a percentage-wise compensation policy by the government succeeds in diminishing the heterogeneity among players. According to the experiments, the best responses get a more stable feature. The pay-offs for the players still differ based on the experience level, but the probabilities of winning converge. Despite the long-term societal value of the compensation, it comes at a cost for the government that could be partly offset by the diminished mark-ups, but a trade-off should be made concerning to what extent they want to increase competition in the PPP market.

Extending our view towards a four-player bidding environment, the reimbursements do not succeed in incentivizing all inexperienced players to enter the market with a reasonable investment. The two-player case suggests lower reimbursement percentages in low-risk projects and Figure 4.6 indicates that the competitive forces deliver enough incentives for reasonable pre-tender investments for all players which makes the introduction of reimbursements to equalize the market obsolete and it would only inflate government expenses.

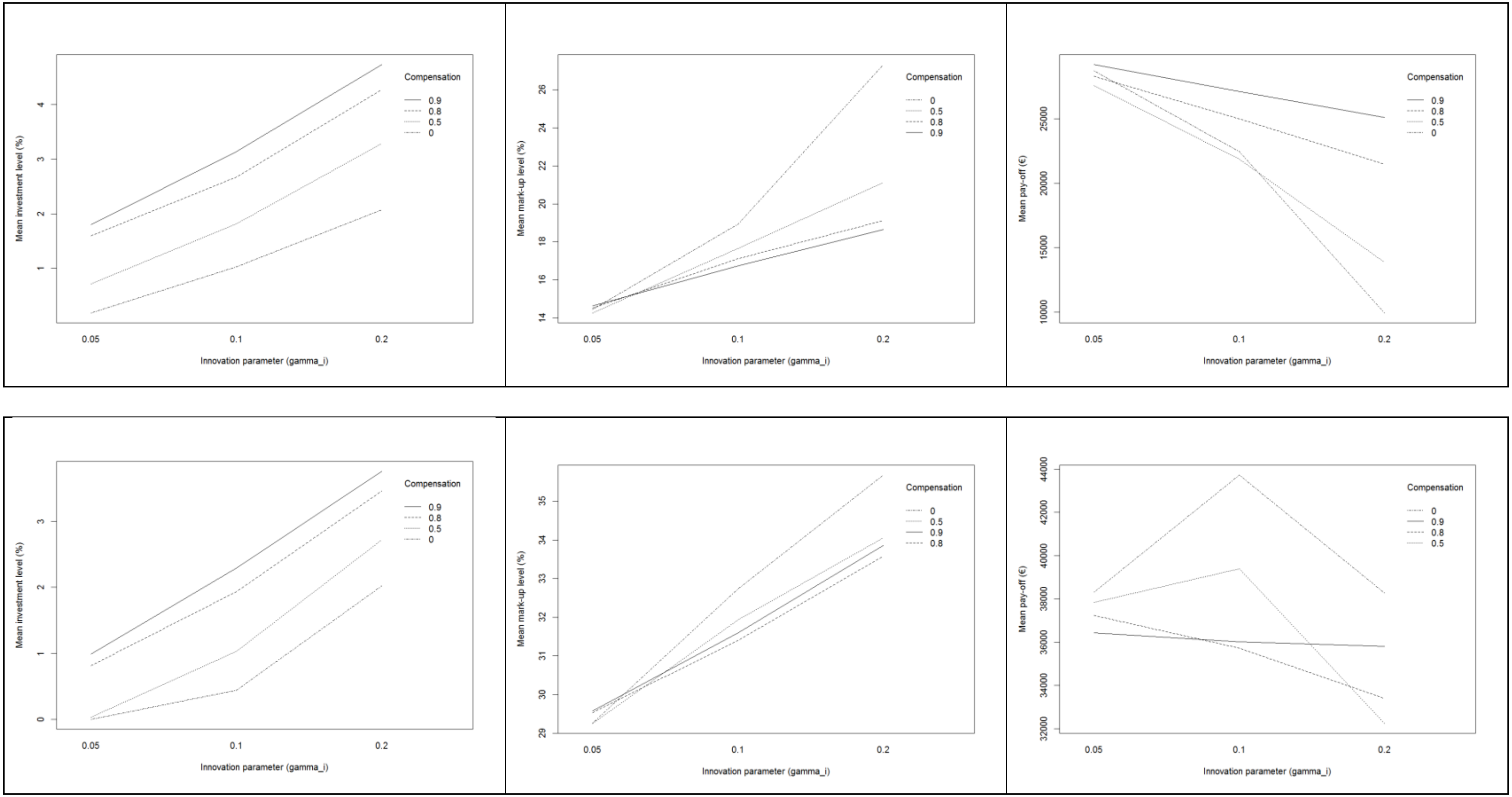


Figure 4.7 [strategy game algorithm] The interaction between the innovation parameter $\gamma_i$ and the government compensation level $d$ with the investment level, the mark-up level and the pay-off for the scenarios in which $\sigma$=5% (upper pane) $\sigma$=15% (lower pane)

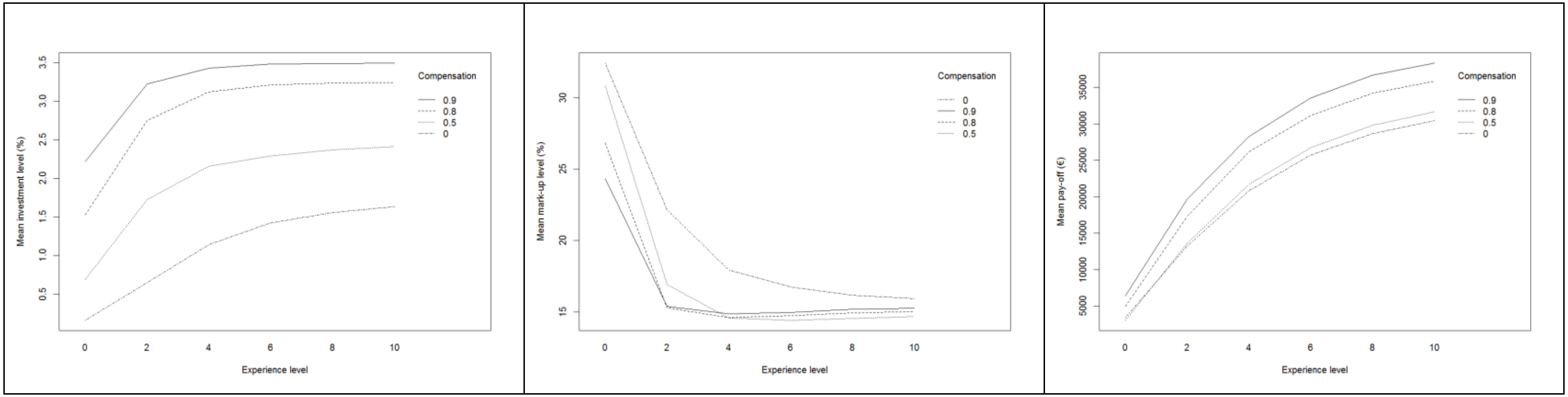


Figure 4.8 [strategy game algorithm] The interaction between the experience level $e_1$ and the government compensation level $d$ with respect to the investment level, the mark-up level and the pay-off for the scenarios in which $\sigma$=5%

### 4.4.5 Other findings and robustness tests

With respect to the simulation experiments, the effects of an increase of the efficiency parameter $\beta_e$ and the uncertainty due to an experiential lack $\gamma_e$ mainly affect less experienced players and amplify the divergence in the strategic behavior. A ceteris paribus surge in the learning rate parameters $\lambda_e$ and $\lambda_i$ makes players more eager to invest faster, but reaching an investment ceiling that is lower (Table 4.4).

The assumptions are in line with industrial tendencies and the extensive sensitivity analysis contributes to the robustness of our findings. Nevertheless, in order to capture the possible asymmetry of the project cost, a gamma distribution has been implemented for which the shape parameters were calculated in line with the set-up of Section 3.5. No significant differences in the dynamics were found. The major difference lies in the higher equilibrium mark-ups and greater expected pay-offs. Secondly, contractors could have risk averse behavior and prefer another strategy on the efficient frontier that guarantees a smaller expected pay-off but with a smaller standard error. If all contractors have equal preferences, the conclusions remain valid. A different discretization of strategies in the algorithms only modifies the results in the sense of the magnitude of the impact, while the general dynamics are consistent.

## 4.5 Conclusion

This chapter executed the first computer experiments on the proposed PPP tendering procedure that has been translated into an auction format in which a contractor, who is characterized by a level of experience, determines the amount of money to invest in research and which mark-up is applicable. This chapter considers a single-project setting. Monte Carlo simulations simulate the bidding outcome and the resulting pay-off functions while approximation algorithms are developed to identify the Nash equilibrium.

The heterogeneity of the contractors has an important impact on the bidding equilibrium. Especially new entrants have difficulties to enter an already mature market if the project has a high degree of complexity and risk. The theoretical model advises governments to limit the number of players that are invited for the tender. On the other hand, a two-player environment can result in oligopolistic behavior. Instead, a three-player environment seems to work well. The theoretical model supports that a reimbursement of bidding costs, if properly designed, can help in opening up the market in the long run. The models suggest compensation levels of 80% which is a high fraction, but not uncommon in French and Canadian jurisdictions (KPMG 2010). Nevertheless, compensations create the largest added value in high-risk three-player environments. This compensation seems to be less necessary in low-risk projects and it could even lead to opportunistic bidding behavior. Three concise policy recommendations summarize this chapter:

- The government should control the competition in heterogeneous markets through an appropriate funneling strategy.
- A reduction of the complexity results in more incentivized bidders and lower costs and attempts to reduce bid costs and to standardize processes could therefore pay off.
- In complex projects, bidding cost reimbursements succeed in leveling the playing field and increasing competition.

The findings and recommendations stated in this chapter mainly relate to public policy decision-making. Nevertheless, moving the scope towards the contractors, the optimal strategies themselves prescribe how to behave within a particular market. In an attempt to concisely list some recommendations for the private sector, we could claim:

- Due to the winner's curse, high-risk projects are dangerous territory for inexperienced contractors. Especially, when two other and more experienced contractors are prequalified, it might be beneficial to refrain from participating when no bid compensations are attributed. Consequently, it might be safer to enter a new jurisdiction via low-risk tenders.

- For a consortium, it is important to assess the competitive position in the bidding field as this determines the bidding behavior. With a competitive advantage, it is beneficial to engage in larger investment efforts and lower mark-ups.
- Also the effect of the compensation needs to be nuanced. High investment efforts are only recommended when the compensations are sufficiently high.

# Chapter 5 An *ex ante* strategy model

## 5.1 Introduction

According to a consultancy report and supported by empirical evidence in Canada for instance, a pipeline of projects would contribute to a PPP market's attractiveness (KPMG 2010). In this dissertation, a pipeline is defined as follows:

*A PPP project pipeline is a sequence of similar projects that the government ensures to tender in the near future. It may concern totally independent projects or sub-projects that serve a larger purpose.*

This pipeline, also referred to as the project agenda, reduces the consortium's risk of being unsuccessful, because instead of putting all one's eggs into one basket, a consortium can spread out its investments across different projects and it can offset former losses in future tenders. A contractor or consortium might be more willing to enter a market in which there is a certainty for future projects. Moreover, winning a project in this jurisdiction could result in increased experience and a better credibility status which might lead to a competitive advantage in future tenders. However, due to the high cost and the extensive time frame of PPPs, the project pipeline usually has only a limited nature. Governments change and long-term public budgets are difficult to predict.

This chapter extends the model of Chapter 4 by including a pipeline of projects into a theoretical multi-project procurement model. The pipeline of projects is assumed to be publicly communicated and confirmed. Referring to assumption 9 of Section 3.2, the PPP projects that are considered by the contractors have a similar nature in the sense that they have equivalent cost and risk characteristics. For instance, we could say that these projects are all toll road infrastructure projects or all social housing projects within the same jurisdiction.

The purpose of this chapter is to determine an *ex ante* strategy for the contractors or consortia in this bidding setting. The *ex ante* strategy is going to prescribe for a given project pipeline, how to spread out the bidding efforts over these projects, under the assumption that we cannot change our behavior once the preferred bidder has been selected for one of the projects. While Chapter 6 does consider the possibility to modify the actions based on the fact whether you have won or lost previous tenders, the framework of this chapter does not reveal this information along the pipeline.

This *ex ante* setting is useful for two reasons. Firstly, the tendering procedure is often time-consuming and therefore, contractors often need to undertake bid preparations for several projects at the same time. Figure 5.1 presents an example of a setting in which the tendering procedures of three projects are overlapping. The expression of interest stage (EOI) and the bid preparation stages overlap for the different projects. A second reason relates to the fact that organizing a consortium involves fixed costs that may be depreciated across multiple projects. In this vein, an *ex ante* strategy for a bidder is defined by a budgeted bid preparation effort (i.e., the investment decision) and a budgeted mark-up percentage (i.e., the mark-up decision).

Under the assumptions of the model, we address the following questions:

- How does the optimal bidding strategy change when there are several project opportunities?
- How do these dynamics interplay with the project characteristics and the bidding environment?

- How could these dynamics be translated into policy measures for the government?

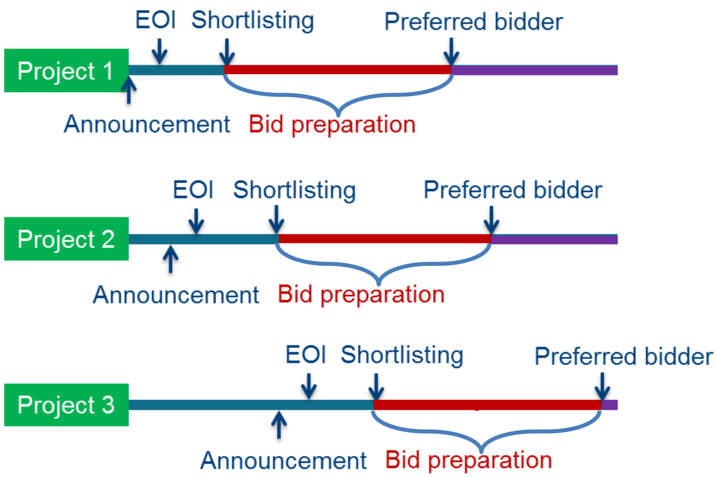


Figure 5.1 Example of a project pipeline timeline

This discussion not only contributes to the academic PPP procurement literature in which these multi-project settings have hardly been discussed, but also relates to the procurement auction literature. The model combines heterogeneity among the bidders and uncertainty in the project outcome with a multi-unit auction format without information revelation.

From a managerial perspective, we give a theoretical argument that supports the practitioner's expectation of cheaper contracts in case of a project pipeline. This chapter adds the new finding that the length of the pipeline does not need to be extensive, but cementing a short-term pipeline enhances the competitive forces from a pricing perspective. The impact on the expected investment efforts is shown to be not straightforward. However, standardization that could lead to transferable investments might incentivize consortia to incur larger investments earlier in the pipeline.

## 5.2 Literature review

Since Section 4.2.2 discussed the peculiarities of the PPP bidding model with respect to the academic auction literature, this heading focuses on the dynamic aspects of the *ex ante* model that is presented in this chapter. The multi-unit auction theory is particularly intertwined with the study of the competitive PPP procurement model with a pipeline of projects.

It is important to denote the difference between competitive bidding and auctions. The former setting mainly refers to procurement and focuses on the lowest bids or the most advantageous tenders in a multi-criteria decision process, while the latter usually refers to selling objects to the highest bidders.

On the one hand, within an auction setting, multiple units might be auctioned simultaneously, so that bidders could bid on different packages of objects. This setting is referred to as a combinatorial auction. Next to applications in electricity markets (Triki et al. 2005) and procurement markets (e.g., Chilean school meals in Catalán et al. 2009) on the public side, also the transportation (Triki et al. 2014) and retail industry (Aissaoui et al. 2007) could rely on the combinatorial auction mechanism. Supported by the growth of online auctions, this combinatorial auction design has received considerable attention within the operations research community (e.g., de Vries and Vohra 2003, Pekeč and Rothkopf 2003, Olivares et al. 2012).

On the other hand, auctioning might be organized in a strictly sequential fashion. The *ex ante* model does account for the sequential nature of the tendering procedures but includes the notion that the tendering processes are overlapping or that project outcomes are still uncertain at the time of budgeting. Within the sequential auction field, an important question relates to the price trend of the objects in the sequence. Although Weber (1983) proved that bids follow a Martingale in the case of an uncertain common value, the majority of studies claims that bid prices are declining. Examples include von der Fehr (1994) who studies auctions with a participation cost, Jeitschko (1999) for the case where the second auction only occurs with an exogenous probability and Kannan (2010) in a setting with complete bid revelation. Branco (1997) supports the price decline in the case of complementarities between identical objects, which is nuanced by Sørensen (2006) in the case of a large number of stochastically equivalent objects or when probabilities to draw a large value are high. The declining price effect is usually attributed to the decreased competition in later stages due to capacity constraints. Engelbrecht-Wiggans (1994), however, relates the cost trend to the cost distribution of the stochastically equivalent objects. As long as the sequence progresses and given that the participants only request a single unit, competition reduces, but the author introduces a second effect that is related to the number of remaining chances to win and meet the one-unit demand. Additionally, Menezes and Monteiro (2004) claim that the trend depends on the synergies of the objects. Although we do not account for capacity constraints in this dissertation, our setting supports these findings from a procurement perspective. The players' ex ante strategies consist of lower mark-ups for earlier projects in the pipeline, thus resulting in more aggressive bidding in early stages. Finally, the laboratory experiment of Soo and Oo (2014) renders that the bidding behavior in the construction industry is dependent on the market trend with more aggressive bidding in times of recession than in an environment with a booming number of contract opportunities.

In general, sequential auction studies could be categorized according to dimensions related to the objects' and bidders' characteristics. In order to guarantee the analytical manageability, a lot of studies limit themselves to a two-stage model (e.g., Branco 1997, Elmaghraby 2003, De Silva et al. 2005, Zeithammer 2009, Reiβ and Schöndube 2010, Jofre-Bonet and Pesendorfer 2014), while other formats look at Markov strategies in more extensive finite sequences (e.g., Katehakis and Puranam 2012, Takano et al. 2014) or account for an infinite time frame (e.g., Oren and Rothkopf 1975, Zeithammer 2007, Hörner and Jamison

2008, Said 2011). In line with experience from practice, the PPP pipeline has a finite nature. This is due to the magnitude of the projects and the fact that government budgets have a limited time horizon. Another object-related dimension concerns the relationship between the auctioned objects. The objects can have a homogeneous nature in the sense that they are perfect substitutes (Katzman 1999, Zeithammer 2009) or stochastically equivalent (Engelbrecht-Wiggans 1994, Reiβ and Schöndube 2010, Said 2011). Alternatively, synergies or the complementary feature of objects has proven to significantly influence strategic behavior (Branco 1997, Benoit and Krishna 2001, Menezes and Monteiro 2004, De Silva et al. 2005). The PPP model accounts for experience and learning effects, so that more competition could be expected in earlier stages of the game.

An additional set of dimensions is related to the bidders. On the one hand, the capacity constraint diversifies the modelling approaches. The contributions of Milgrom and Weber (1982[b]), Engelbrecht-Wiggans (1994), Elmaghraby (2003) and Reiβ and Schöndube (2010) are limited to a single-unit demand, while Katzman (1999), Jofre-Bonet and Pesendorfer (2003) and Katehakis and Puranam (2012) allow for the procurement of as many items as possible. Other models have constraints in the monetary capabilities (Pitchik 2009) or in the availability of man-hours (Takano et al. 2014). Subsequently, the research topics can be differentiated according to the identity of the bidders. Most papers deal with the same set of contractors and often only take two bidders into account. At the other end of the spectrum, Jofre-Bonet and Pesendorfer (2003), Yildirim (2004) and Said (2011) allow for the entry of new buyers. With respect to this chapter, the PPP model reduces complexity in the sense that it only considers a limited number of suppliers and situations without capacity constraints.

Last but not least, for the purpose of this setting it is important to look how the sequential auction theory deals with heterogeneity among the bidders. Maskin and Riley (2000) argue that asymmetric auctions are generally not tractable with analytical methods. In a sequential auction, asymmetries could occur in a second auction because of differences in the completion cost between the bidder that has won the first auction and the other players (Jofre-Bonet and Pesendorfer 2014). Empirical research has studied the complementarity of contracts, like Wolfram (1998) for sequential electricity contracts with start-up prices, Anton and Yao in the defense sector and De Silva et al. (2005) for road infrastructure contracts. The asymmetry in these cases is an endogenous consequence. Nevertheless, dealing with exogenous heterogeneity is rare. However, Reiβ and Schöndube (2010) start with differences in the project completion cost in the context of two sequentially tendered, stochastically equivalent projects and capacity constraints and describe the deviation from the standard independent private value auction. The PPP model also allows for exogenous heterogeneity, meaning that bidders may have a cost advantage (i.e., a smaller expected cost) and a knowledge advantage (i.e., a smaller variance of the cost probability distribution) at each stage of the game.

## 5.3 Methodology

From a methodological perspective, this chapter is greatly comparable with the procedure in Chapter 4 for the single-project setting. This section covers the extensions of the model to a multi-project setting with overlapping bid preparations. The introduction of a pipeline of projects results in the proliferation of decision variables.

### 5.3.1 The *ex ante* model

As explained in the introduction, the consortia are looking into an *ex ante* strategy when they think about how to spread their investment budget over the announced pipeline of projects in the near future. Each PPP project requires large research and development exertions. Moreover, one should think about the synergies and economies of scale that can be realized when multiple projects are part of a consortium’s portfolio. Engaging in multiple projects can also be a way of mitigating the risk, because suffered losses in one project might be recovered by profits in other projects.

As this chapter deals with overlapping tendering processes, we actually have an auction format without information revelation so that contractors are not able to (easily) modify their strategy along the pipeline. From a game-theoretic perspective, this is a simultaneous game, which means that a contractor's *ex ante* strategy is based on the expected beliefs whether he or she will win or lose a project before moving to the next project in the pipeline. Alternatively, the fully dynamic model of Chapter 6 assumes full information revelation with respect to who has won the project at each stage, which requires a different approach in finding the optimal strategy. In practice, the most appropriate model will be a combination of both worlds.

In order to deal with the increased complexity of the multi-project setting, a number of additional modelling assumptions has been introduced in Section 3.2 with respect to the characteristics of the pipeline and the identity of the bidders (assumptions 8 to 10). In brief, we assume that the initial experience vector $e = (e_1, e_2, \dots e_P)$ is common knowledge. Moreover, the set of shortlisted bidders remains constant over the pipeline, which means that the number of bidders stays the same, so no bidders leave or enter the game. Additionally, the outcome of the tender only affects the experience levels. With respect to the projects, we assume that the projects of the pipeline have a similar nature. What is meant by that is that, without considering experience or the investment efforts, all projects are stochastically equivalent (i.e., have the same parameters for the knowledge impact and the direct cost impact assumptions). Assumptions 1-7 of Section 3.2 are also applicable in this chapter. In the *ex ante* model, the contractors could anticipate the fact that a future experience increase results in synergies. The direct cost impact results from economies of scale (e.g., expensive machinery that could be depreciated over different projects) and the knowledge impact benefits from risk synergies (i.e., a portfolio of risks is less perilous than the sum of its individual risk fractions).

Given is a sub-game $e = (e_1, e_2, \dots, e_P)$ taking into account a discrete number of experience levels ranging from zero (i.e., no experience) to ten (i.e., maximum experience). In a sub-game $e$, contractor $p$ determines the optimal strategy $s_p^*$ for the entire project pipeline with $Z$ projects. An *ex ante* strategy $s_p$ is composed of two decisions for each project $z \in \{1, 2, \dots, Z\}$ in the pipeline: an investment decision $i(s_p^z)$, that is expressed as a percentage of an initially set project cost base, and a mark-up decision $m(s_p^z)$, that is expressed as a percentage value and which is applied to the estimated project cost. The strategy for player $p$ is represented by a vector $s_p = \left(i(s_p^1), m(s_p^1), i(s_p^2), m(s_p^2), \dots, i(s_p^Z), m(s_p^Z)\right)$. Recall the dual impact of pre-tender investment: it leads to more accurate cost estimates, reducing the project risk, and innovations or efficiencies could directly decrease the expected project cost (Martzoukous and Zacharias 2013, Lippman et al. 2013). Each contractor simultaneously determines his optimal strategy, so it is in our goals to identify the bidding equilibria. A (Bayesian) Nash equilibrium strategy profile $s^* = (s_1^*, s_2^*, \dots, s_P^*)$ for sub-game $e$ refers to the combination of strategies for the players in which none of the bidders has an incentive to deviate from his current strategy choice $s_p^*$ given the strategy combination of his opponents $s_{-p}^*$, or mathematically expressed in equation (3.1).

Concerning the composition of the vector $s_p$, two mechanisms are studied in this chapter: the consistent strategy model (CSM) and the variable strategy model (VSM). The VSM allows for a different investment percentage and mark-up percentage for each project or stage $z$ in the game. While this allows for more flexibility in the decision options, the number of strategies explodes when more projects are included in the pipeline. Alternatively, the CSM imposes that a contractor selects a single investment percentage and a single mark-up percentage that is applied to all projects in the pipeline. This simplifies the study of longer pipelines as the strategy vector now only consists of two elements: $s_p = \left(i(s_p), m(s_p)\right)$. In each stage $z$, the same investment $i(s_p)$ and mark-up $m(s_p)$

are applied. However, this disregards any flexibility in defining project-specific investment and mark-up levels, so we should better consider these figures as the average budgeted investment and the average budgeted mark-up percentage.

### 5.3.2 Hypotheses

This chapter assesses how the introduction of a project pipeline, i.e., creating a trustworthy project agenda with multiple consecutive projects, triggers a change in the strategic behavior. The conclusions from consulting reports (KPMG 2010) and interviews with practitioners raise several hypotheses that are theoretically tested.

Firstly, practitioners claim that the creation of a pipeline would be a trigger to be more competitive for the projects earlier in the pipeline. This is based on the rationale that a contractor hopes to acquire an established position in the market. From the literature review, it is clear that in most cases the competition is fiercer in the earlier stages of the sequential auction. Therefore, it seems essential to test whether the project proposals become cheaper in the case more projects are added to the pipeline. Additionally, we need to investigate whether the model supports the intuition that project proposals would also become of a higher quality. The majority of the interviewees believe that a higher quality proposal is ought to be expected (Section 7.2.4). However, a large international investment company claimed that they are sometimes willing to reduce mark-ups to the lower limits and play on the price aspect, in order to grasp some essential experience in a particular jurisdiction. To the best of our knowledge, there are no academic, theoretical results whether this would be the case. Hence, this raises the following hypotheses:

*Hypothesis 1: In equilibrium, the investment efforts of the contractors are expected to be higher if the number of projects in the sequence is greater.*

*Hypothesis 2: In equilibrium, the mark-up levels are expected to be decreasing if the number of projects in the sequence is greater.*

Chapter 4 showed that a large number of shortlisted bidders could inhibit some contractors to prepare a proposal. Nonetheless, one could expect that if these bidders have also future opportunities to win contracts, the competitive forces are reestablished. Chapter 4 also concluded that the fact that governments reimburse losing bidders for the bidding effort might level the playing field, leading to more competition. Now, we consider the pipeline as a trigger for incentive creation. Eventually, this might make the impact of the investment reimbursements obsolete. Hence, the next hypothesis is formulated:

*Hypothesis 3: In equilibrium, a larger number of projects in the pipeline stimulates the participation of the players. As a consequence, government compensation policies to create a more competitive market are less essential.*

Finally, as bidders face fiercer competition after the introduction of the pipeline, this should also lead to lower procurement expenses for the government.

*Hypothesis 4: The average expected project procurement cost for the government decreases if the number of projects in the pipeline increases.*

### 5.3.3 Analytical background

Given is a project pipeline with $Z$ projects, a $P$-player subgame with initial experience vector $e = (e_1, e_2, \dots e_P)$ and a strategy profile $s = (s_1, s_2, \dots, s_P)$ in which each $s_p$ with $p \in \{1, \dots, P\}$ refers to player $p$'s strategy, expressed as a vector $s_p = \left(i(s_p^1), m(s_p^1), \dots, i(s_p^Z), m(s_p^Z)\right)$. For this project pipeline and this strategy profile, the expected pay-off vector is dependent on the expected instantaneous pay-off (as defined in Section 3.4) calculations of all projects in the pipeline. The outcome for the first project is straightforward, but the expectation of the second project will depend on who has won the first project, so that $P$ scenarios are created for the second project. For the third project, $P^2$ scenarios need to be considered. The total expected pay-off $\pi_p(s|e)$ for player $p$ in sub-game $e$ and a three-project environment with *ex ante* strategy profile $s$ is decomposed as follows:

$$\pi_p(s|e) = \sum_{j=1}^{P}\sum_{k=1}^{P} q_j^1(s|e)q_k^2\left(s\middle|e,y_j^1=1\right)\left(\rho_p^1(s|e)+\delta_1\rho_p^2\left(s\middle|e,y_j^1=1\right)\right.$$
$$\left.+\,\delta_2\rho_p^3\left(s\middle|e,y_j^1=1,y_k^2=1\right)\right)$$

with: (5.1)

- $q_j^z$ is the probability that player $j$ wins project $z$;
- $y_j^z$ is a binary variable that has value 1 if player $j$ has won project $z$ and indicates that the experience level of player $j$ is increased;
- $\pi_p^z$ refers to the pay-off for player $p$ in the tender for project $z$;
- $\delta_{z-1}$ equals a discount factor to account for the time value of money.

Consequently, the expected total pay-off is a linear combination of the instantaneous pay-offs for all the possible combinations of experience levels that could be encountered along the pipeline. Section 6.3.2 introduces a more general formulation for the expected pay-off. The expected pay-off consists of an instantaneous pay-off of the first project together with a continuation value for the later projects of the pipeline. As this understanding is not essential for the simulation and optimization setting of the *ex ante* model, we will leave this discussion for Chapter 6 that introduces the specific jargon of the sequential game with Markov perfect strategies.

The analytical characterization of the instantaneous pay-off $\rho_p(s|e)$ is analogue to what has been described in Section 3.4. Nevertheless, the instantaneous pay-offs are now dependent on the history of the players. The history includes the information on who has won projects earlier in the pipeline. This means that the given experience vector $e$ is only applicable for calculating the instantaneous pay-off of the first project in the pipeline. The other instantaneous pay-offs take into account the intermediate experience levels $\bar{e} = (\overline{e_1}, \overline{e_2}, \dots, \overline{e_P})$. Moreover, at each stage of the game also the appropriate investment and mark-up percentages need to be selected to be inserted in equations (3.2) to (3.6) In Chapter 6, we refer to the combination of the stage-specific investment and mark-up as the *action*. In the CSM, this is pretty straightforward as this model only considers an average investment and mark-up choice for the entire pipeline, so that for the equations of Chapter 3: $\bar{s} = (\overline{s_1}, \overline{s_2}, \dots, \overline{s_P})$ with $\overline{s_p} = \left(i(s_p), m(s_p)\right)$. The VSM, on the other hand, allows for different decisions for each stage $z \in \{1, \dots, Z\}$. Hence, the expected pay-off calculations require $\bar{s} = (\overline{s_1}, \overline{s_2}, \dots, \overline{s_P})$ with $\overline{s_p} = s_p^z = \left(i(s_p^z), m(s_p^z)\right)$. In summary, the latter case means that the appropriate investment and mark-up level for this particular stage need to be selected. Recall that in this *ex ante* framework, the strategy is only dependent on the stage of the game and independent of which player has won or lost earlier projects in the given pipeline (which is referred to as a *state* in Chapter 6). That is due to the fact that, from an *ex ante* perspective, the bidder does not have the opportunity to modify the strategy based on newly available information.

Following the rationale to derive the total expected *ex ante* pay-off $\pi_p(s|e)$ as in equation (5.1), all players simultaneously optimize this function. In the case of the CSM, only a single investment and a single mark-up percentage optimize the total expected pay-off for each of the $P$ players and therefore lead to the following system of $2P$ equations, which is identical to the single-project setting:

$$\begin{cases} \partial\pi_p(s^*|e)] \big/ \partial i(s_p^*) = 0 \\ \partial\pi_p(s^*|e) \big/ \partial m(s_p^*) = 0 \end{cases} \qquad \forall p \in \{1,2,\dots,P\} \tag{5.2}$$

In the case of the VSM, a system of $2ZP$ differential equations needs to be solved:

$$\begin{cases} \partial\pi_p(s^*|e)] \big/ \partial i(s_p^{z*}) = 0 \\ \partial\pi_p(s^*|e) \big/ \partial m(s_p^{z*}) = 0 \end{cases} \quad \forall z \in \{1,2,\dots,Z\}, \forall p \in \{1,2,\dots,P\} \qquad (5.3)$$

### 5.3.4 Simulation model

An identical reason as in the previous chapter motives the use of simulation in the *ex ante* framework. Instead of exactly calculating the expected pay-off for a presumed distribution, the simulation reduces computation times and allows to gain insights into the distribution of the pay-offs for any given distribution. Especially now that multiple projects need to be studied, the computation times for exact calculations for the total expected pay-off of a pipeline surge. Essentially, the procedure of the simulation is completely in line with the description in Section 4.3.2, but each iteration is now extended for the multi-project setting.

The inputs for the procedure consist of the initial (i.e., at the time of tendering the first project) experience vector $e = (e_1, e_2, \dots, e_P)$ and an *ex ante* strategy profile $s = (s_1, s_2, \dots, s_P)$ with an *ex ante* strategy $s_p$ representing the investment and mark-up choices for all projects in the pipeline and represented by $s_p = \left(i(s_p), m(s_p)\right)$ in the CSM or $s_p = \left(i(s_p^1), m(s_p^2), \dots, i(s_p^Z), m(s_p^Z)\right)$ in the VSM. Section 3.5 translates the knowledge impact assumption resulting from the project's complexity and the direct cost impact assumption resulting from innovations and efficiency gains in equations (3.5) and (3.6) respectively. The output of the simulation procedure is a pay-off distribution for each bidder. The average pay-offs for the strategy profile $s$ are given by the pay-off vector $f = \left(f_1(s|e), f_2(s|e), \dots f_P(s|e)\right)$ which is an approximation of the expected pay-off vector $\pi(s|e) = \left(\pi_1(s|e), \pi_2(s|e), \dots, \pi_P(s|e)\right)$ with $\pi_p(s|e)$ as derived according to the rationale to arrive at equation (5.1).

In order to determine the pay-off distributions of a particular strategy profile, a user-defined number of iterations $m$ is performed. A single iteration passes through the entire project pipeline. The input for the first project is $e = (e_1, e_2, \dots, e_P)$ and the investment and mark-up decisions $i\left(s_p^1\right)$ and $m\left(s_p^1\right)$ for the first project. Consider Gaussian cost and bidding distributions. The reference actual cost $\tilde{A}^1$ is a random variable that is drawn from the distribution $N(\mu, \sigma_u^2)$ with $\mu = €\ 1{,}000{,}000$ and $\sigma_u^2 = (\mu\sigma)^2$ and that is the same for all players. The final actual cost is different, because it is related to the particular cost distribution of the winner of the tender. The (unknown) actual project cost for $p$ results then from the linear transformation $\tilde{A}_p^1 = \tilde{A}^1(1 + g_p)$, which is set to the mean of the cost probability density $c_p^1$ for player $p$. Hence, $c_p^1$ is a nested distribution of the form $N\left(\mu\left(1 + g_p\right), \left(1 + g_p\right)^2\left(\sigma_u^2 + \sigma_p^2\right)\right)$. The contractor's estimated cost $\widetilde{C_p^1}$ is randomly selected from $c_p^1$ and eventually, a contractor applies the mark-up level $m_1(s_p)$, resulting in the bid: $\widetilde{B_p^1} = (1 + m_1(s_p))\widetilde{C_p^1}$. The minimum of these simulated bids is the winning proposal and its pay-off is determined, where the actual cost is $\widetilde{A_w^1}$ for winner $w$. The losers' pay-offs equal the fraction of the pre-tender investments that is not reimbursed by the government. The winner's experience level needs to be increased, resulting in a new experience vector $e'$ and the procedure is repeated for the second project and the resulting pay-offs are discounted with the discount factor $\delta_{z-1} = \frac{1}{(1.05)^{z-1}}$ and accumulated. The iteration finishes as soon as all projects from the pipeline have been tendered and then the next iteration starts.

### 5.3.5 Equilibrium approximation algorithm

In order to maintain the manageability of the model, we favor a discretization of the decision variables. The multi-project setting causes a proliferation of strategies in the VSM. $I$ investment choice, $M$ mark-up choices, $P$ players and $Z$ projects result in in $(IM)^{ZP}$ strategy profiles in the VSM. The CSM, on the contrary, only has $(IM)^{P}$ strategy profiles regardless of the number of projects.

Apart from the number of strategies and the simulation model that takes the sequence of projects into account, the algorithm to approximate the best response in equilibrium is analogue to the strategy game algorithm explained in Section 4.3.3.2 and the pseudo-code in Appendix B. The only difference is that when an expected pay-off calculation is performed, the experience vector and strategy profile are sent to the multi-project simulation procedure of Section 5.3.4.

### 5.3.6 Experimental setting

The algorithms have been implemented in Microsoft Visual Studio 2010. Table 5.1 lists the parameter values that have been tested in this experimental study and that are covered in Sections 5.4.1 and 5.4.2. Each combination of the parameter settings is referred to as a scenario. With respect to the discretization of the problem, Table 5.2 tabulates the determinants of the CSM and the VSM. As is clear from the table, the study of the VSM is limited in the number of projects of the pipeline and the considered strategies, since the flexibility adds complexity to the model. The equilibrium approximation algorithm reports the equilibrium strategy response for the first player, with experience level $e_1$ of a given experience vector $e = (e_1, e_2, \dots, e_P)$. We refer to the vector $e_{-1} = (e_2, \dots, e_P)$ as the bidding situation for which we determine the equilibrium response of player 1. The number of experience intervals $e_u$ equals five, so that the contractors move on the scale from 0 to 10 in steps of 2 in case of a win. The values of the tuning parameters of the strategy game algorithm itself are equivalent to those in Table 4.3.

| Parameter | Interpretation | Values (Section 5.4.1) | Values (Section 5.4.2) |
|---|---|---|---|
| $\sigma$ | Uncontrollable project risk | 0.05 | 0.05 |
| $\gamma_e$ | Maximum risk impact of a lack of experience | 0.05 | 0.05,0.1 |
| $\gamma_i$ | Maximum risk impact of a lack of investment | 0.1,0.2 | 0.05,0.1,0.2 |
| $\lambda_e$ | Experiential learning rate | 0.25 | 0.25 |
| $\lambda_i$ | Investment learning rate | 0.25 | 0.25 |
| $\beta_e$ | Experiential cost disadvantage | 0.1 | 0.05,0.1 |
| $\beta_i$ | Investment cost disadvantage | 0.05 | 0.05 |
| $\mu_e$ | Experiential cost decrease rate | 0.25 | 0.25 |
| $\mu_i$ | Investment cost decrease rate | 0.25 | 0.25 |
| $d$ | Government compensation level | 0,0.1,0.2,…,0.9 | 0,0.3,0.6,0.9 |
| $\delta_z$ | Discount rate | 1/1.05 | 1/1.05 |

Table 5.1 Parameter values used in the experimental study

| | Consistent strategy model | Variable strategy model |
|---|---|---|
| Number of investment levels *I* | 11 | 6 |
| Investment levels | 0%,1%,2%,…,10% | 0%,2%,4%,…,10% |
| Number of mark-up levels *M* | 51 | 6 |
| Mark-up levels | 0%,1%,2%,…,50% | 0%,10%,20%,…,50% |
| Number of players *P* | 2,3,4 | 2,3 |
| Experience levels | 0,2,4,6,8,10 | 0,2,4,6,8,10 |
| Number of projects *Z* | 1,2,3,4,5 | 1,2,3 |

Table 5.2 Model characteristics in the experimental study

## 5.4 Experimental results

The interest of this chapter lies in the impact of increasing the number of projects to be tendered on the strategy equilibrium. Moreover, we are interested in how the dynamics that have been discussed in the single-project model are amplified or fade out due to the introduction of a pipeline. Hence, the *ex ante* strategy equilibria are compared for each scenario when the number of projects in the pipeline is increased.

Consequently, the outcomes consist of paired observations and the paired samples t-test is used to study the differences. Three assumptions are important for the paired t-test: random sampling, normal distribution of the response variables and interval or ratio data. The paired t-test is rather robust for the normal distribution assumption. However, we are dealing with experimental data with only a limited number of discrete strategies and one should be careful for applying the parametric paired t-test. Therefore, the equivalent non-parametric Wilcoxon signed rank test has been used, but the findings are identical.

A final remark relates to the fact that we might be unable to identify marginal results due to the discretization of the strategies. Section 5.4.1 defines a base case that aims to extend the discussion of the bid cost reimbursement towards the multi-project setting. Section 5.4.2 additionally adds changes in the other model parameters of the VSM.

### 5.4.1 Base case analysis

Motivated by the practical importance of the assessment of governmental policies, this section looks into the impact of the introduction of extra projects and bid cost reimbursements in a low-risk ($\gamma_i = 0.1$) and high-risk ($\gamma_i = 0.2$) base case scenario. In this base-case scenario, the investment mainly has a knowledge impact and the experience merely has a cost impact (Table 5.1).

#### *5.4.1.1 Consistent strategy model*

Table 5.3 reports the average investment and mark-up differences over all scenarios in the CSM experiment, that deals with a strategy as an average investment and mark-up level for an entire pipeline, with the number of projects going from one to five. With respect to the investment levels, there is statistical significance in favor of decreasing investments in the four-player case, but the economic significance is little. Additionally, the results show a significant positive investment impact for three players in the low-risk base case. This result is mainly attributed to a 0.11% (p=0.04) and a 0.41% ($p=1.9*10^{-10}$) average investment raise by inexperienced players (i.e., $e_p = 0$) when moving from a single-project to, respectively, a two- and a five- project pipeline. Furthermore, extra projects lead to decreasing mark-up percentages for all players in two- and three-player environments in the CSM, but the four-player result is ambiguous (Table 5.3). This is due to the fact that the decreased mark-ups of experienced players put pressure on the inexperienced players that now tend to stay out of the market, so setting a maximum mark-up in the model. Nevertheless, if the number of players is limited to two or three, the inexperienced players opt for a larger mark-up drop compared to the experienced participants. The impact of the number of projects on the mark-up change is in that case concave and decreasing in the number of projects.

According to the experiments, the response to the introduction of compensations is in line with the findings of Chapter 4, regardless of the number of projects in the pipeline: the most prospering results are obtained in high-risk three-player scenarios. Two-player results show a significant increase in investment, but also a slight increase in mark-ups when compensations are included, while compensations have a convex and increasing investment impact and a concave and decreasing mark-up impact in the four-player case, so that only excessively high and costly compensations have a positive effect. The interaction between the number of projects and the government compensation is only significant in the three-player case of the CSM ($p=0.04$ for investment and $p=1.7*10^{-5}$ for mark-up) meaning that lower compensations already lead to a drop in the mark-ups, making the market more competitive from a pricing perspective.

Consequently, in this conservative CSM approach, the tendency to move towards lower mark-ups becomes already apparent. Moreover, it is mainly the introduction of the second project that causes the largest change. The investment dynamics are not yet clear though. Therefore, the next section fine-tunes these tendencies and looks at the same base case but now from a variable strategy perspective, the VSM. Due to the added complexity that results from the flexibility of applying a different investment and mark-up choice in the subsequent stages of the game, only a two- and three-project pipeline are discussed.

| CSM | Δ in % (p-value) | $\gamma_i$ | $Z = 2$ | $Z = 3$ | $Z = 4$ | $Z = 5$ |
|---|---|---|---|---|---|---|
| $P = 2$ | Investment | 0.10 | 0.0194 (0.6920) | -0.0139 (0.7618) | -0.0750 (0.1036) | -0.0056 (0.9061) |
| | | 0.20 | -0.025 (0.6058) | 0.0139 (0.7643) | 0.0222 (0.6320) | 0.0167 (0.7155) |
| | Mark-up | 0.10 | **-0.4444** (0.0010) | **-0.7083** ($5.5*10^{-7}$) | **-0.8333** ($5.1*10^{-9}$) | **-0.9583** ($2.4*10^{-10}$) |
| | | 0.20 | **-0.6389** ($4.65*10^{-5}$) | **-0.9722** ($7.82*10^{-10}$) | **-1.125** ($1.47*10^{-13}$) | **-1.3056** ($3.04*10^{-15}$) |
| $P = 3$ | Investment | 0.10 | 0.0191 (0.6272) | 0 (1) | **0.0587** (0.0170) | **0.0627** (0.0138) |
| | | 0.20 | -0.0063 (0.8349) | -0.0341 (0.2794) | 0.0317 (0.3214) | 0.0429 (0.1865) |
| | Mark-up | 0.10 | **-0.5476** ($2.6*10^{-8}$) | **-0.8691** ($<2.2*10^{-16}$) | **-1.1468** ($<2.2*10^{-16}$) | **-1.4286** ($<2.2*10^{-16}$) |
| | | 0.20 | **-0.2063** (0.3225) | **-0.4722** (0.0375) | **-1.1349** ($2.35*10^{-6}$) | **-1.4365** ($6.31*10^{-9}$) |
| $P = 4$ | Investment | 0.10 | **-0.0515** (0.0002) | **-0.0378** (0.0057) | **-0.0372** (0.0070) | **-0.0491** (0.0004) |
| | | 0.20 | -0.0301 (0.1342) | 0.0146 (0.4776) | 0.0024 (0.9081) | 0.0304 (0.1414) |
| | Mark-up | 0.10 | **0.3646** ($4.7*10^{-5}$) | **0.3125** (0.0006) | **0.2946** (0.0017) | **0.2307** (0.0158) |
| | | 0.20 | 0.0506 (0.7493) | -0.2083 (0.2013) | -0.2798 (0.0939) | **-0.5804** (0.0006) |

Table 5.3[1] Increase (+) or decrease (-) in the investment and mark-up percentages with associated p-values, with respect to a single-project environment

#### *5.4.1.2 Variable strategy model*

Table 5.4 and Table 5.5 summarize the results for differences in the investment and mark-ups for the first project of the $Z$-project pipeline and for the averages over the given pipeline. The two-player case supports the hypothesis of the investment increase for the first project in a two-project pipeline, but looking at the averages, only the increase in the high-risk environment is significant. Significance disappears though in a three-project environment. While players with a competitive advantage might invest more, inexperienced players (i.e., with $e_p = \{0,2\}$) reduce the investment efforts. An explanation could be that the bidder who determines the *ex ante* strategy has a great belief in at least winning one

[1] In the tables of this dissertation, numbers in bold refer to significant results at the 95% confidence level.

project and in this vein counts on gained experience for which he does not need to invest now. Also for the mark-up change, the drop is more significant for the first project. The high-risk three-player setting leads to an average mark-up increase, because inexperienced players stay out of the market more often.

| VSM | Δ in % (p-value) | $\gamma_i$ | (a) First project w.r.t. $Z = 1$ | | (b) Average of pipeline w.r.t. $Z = 1$ | |
|---|---|---|---|---|---|---|
| | | | $Z = 2$ | $Z = 3$ | $Z = 2$ | $Z = 3$ |
| $P = 2$ | Investment | 0.10 | **0.1611** (0.0158) | 0.0556 (0.5236) | 0.0778 (0.1565) | 0.1000 (0.1489) |
| | | 0.20 | 0.1056 (0.0970) | -0.0556 (0.5428) | **0.125** (0.0230) | 0.1037 (0.1405) |
| | Mark-up | 0.10 | **-2.0278** ($<2.2*10^{-16}$) | **-5.0556** ($<2.2*10^{-16}$) | **-1.2222** ($1.25*10^{-9}$) | **-2.2963** ($4.12*10^{-14}$) |
| | | 0.20 | **-4.1944** ($<2.2*10^{-16}$) | **-6.1111** ($<2.2*10^{-16}$) | **-2.6667** ($<2.2*10^{-16}$) | **-3.8148** ($<2.2*10^{-16}$) |

Table 5.4 Increase (+) or decrease (-) in investment and mark-up percentages, with associated p-values. The choices for the first project of the pipeline (a) and the average choices of the entire pipeline (b) are compared with the single-project strategy.

| VSM | Δ in % (p-value) | $\gamma_i$ | (a) First project w.r.t. $Z = 1$ | (b) Average of pipeline w.r.t. Z=1 |
|---|---|---|---|---|
| | | | $Z = 2$ | $Z = 2$ |
| $P = 3$ | Investment | 0.10 | 0.0413 (0.1959) | 0.0325 (0.2330) |
| | | 0.20 | **-0.1048** (0.0045) | **-0.07619** (0.0196) |
| | Mark-up | 0.10 | **-1.5000** ($<2.2*10^{-16}$) | **-0.6865** ($1.76*10^{-11}$) |
| | | 0.20 | **0.5968** (0.0119) | **0.5595** (0.0039) |

Table 5.5 Increase (+) or decrease (-) in investment and mark-up percentages, with associated p-values. The choices for the first project of the pipeline (a) and the average choices of the entire pipeline (b) are compared with the single-project strategy.

Besides, the VSM supports the finding related to the compensations: there is only interaction between government reimbursements and the number of projects in the three-player case, so that a 60% compensation for instance could give extra incentives for inexperienced players to refrain from investing less when a new project is introduced. Consequently, compensations get a second feature: not only do they level the playing field, but they also inhibit decreasing the *ex ante* investment in the dynamic case. Moreover, the extra expenses that result from the reimbursements are partly offset by the increased price competition in the multi-project setting.

In this vein, Table 5.6 reports the difference between the total expected government cost of the two-project pipeline and the total expected government cost in the case a single project is tendered two times consecutively. In order to make a valid comparison and to translate the single-project government cost into one that is equivalent to the two-project logic, two intermediate results have been developed. For the first project, the initial sub-game is represented by $(e_1, e_2, e_3)$ and the government cost is calculated. For tendering a second project without a former pipeline, three scenarios might have occurred: $(e_1', e_2, e_3)$, $(e_1, e_2', e_3)$ or $(e_1, e_2, e_3')$, for which the prime indicates the updated experience level for the player who has previously won. For the worst case method, the expected government cost of the most expensive sub-game is discounted and added to the cost of the previous project, while for the weighted method an equal probability is attributed to each sub-game.

| VSM | $\gamma_i$ | Worst case method | Weighted method |
|---|---|---|---|
| 2 players | 0.10 | **-36,345** ($1.67*10^{-6}$) | **-27,946** ($4.77*10^{-6}$) |
| | 0.20 | **-69,922** ($7.43*10^{-9}$) | **-58,436** ($2.36*10^{-8}$) |
| | All scenarios | **-49,633** ($3.16*10^{-13}$) | **-43,191** ($9.69*10^{-12}$) |
| 3 players | 0.10 | **-28,282** ($2.58*10^{-15}$) | **-26,026** ($7.01*10^{-14}$) |
| | 0.20 | **-8,326** ($1.64*10^{-6}$) | **-4,172** (0.0037) |
| | All scenarios | **-18,304** ($<2.2*10^{-16}$) | **-15,099** ($1.82*10^{-13}$) |

Table 5.6 Absolute differences and associated p-values in tendering two times a single project or in the case of a two-project pipeline

The expected government cost is significantly lower if there is a project pipeline, regardless of the project risk or the number of players. The absolute values of the differences are greater in the two-player case, especially for risky projects. On the contrary, it are the less risky projects that have a greater contribution to the government cost decrease in the three-player situation. As a result, the more flexible VSM greatly supports the CSM findings. The pipeline concept positively influences the competition from a mark-up perspective. This also leads to a lower government procurement cost than when the government would only communicate about isolated projects without highlighting future opportunities. The impact on the investment is ambiguous, but one could say that inexperienced players will tend to invest less in bid preparation efforts. Consequently, especially in a three-player context, it could be interesting to include bid compensations to fade out this negative effect.

### 5.4.2 Parameter sensitivity analysis for the VSM

The base case analysis of the previous section is limited in its investigated scenarios. The parameter sensitivity section looks into the robustness of the findings if the other model parameters change. The tested parameter values are listed in Table 5.1.

#### *5.4.2.1 Within-strategy dynamics*

The VSM allows for deciding on a different investment and mark-up for the first and the second project. Table 5.7 and Table 5.8 report the dynamics within the optimal strategy and summarize the average differences between the investment willingness percentages and the required mark-up for the first and the second project in the pipeline. In other terms, if the optimal strategy vector is given by $\left(i\left(s_p^{1*}\right), m\left(s_p^{1*}\right), i\left(s_p^{2*}\right), m\left(s_p^{2*}\right)\right)$, this section discusses the difference between $i\left(s_p^{1*}\right)$ and $i\left(s_p^{2*}\right)$ and the difference between $m\left(s_p^{1*}\right)$ and $m\left(s_p^{2*}\right)$. The scenario-by-scenario comparison in the two-player case concludes that the *ex ante* investment percentages are higher for the first project than for the second project.

| 2 players<br>$Z = 2$ | Absolute mean difference | Paired t-test | Wilcoxon test |
|---|---|---|---|
| $i^{avg}(s_1^{2*}) - i^{avg}(s_1^{1*})$ | **-0.0671** | 0.0272 | 0.0273 |
| $\|e_1 = 0$ | -0.1458 | 0.0623 | 0.0631 |
| $\|e_1 = 2$ | -0.0486 | 0.5112 | 0.5113 |
| $\|e_1 = 4$ | -0.0694 | 0.3412 | 0.3413 |
| $\|e_1 = 6$ | **-0.2014** | 0.0057 | 0.0059 |
| $\|e_1 = 8$ | 0 | 1 | 1 |
| $\|e_1 = 10$ | 0.0625 | 0.4142 | 0.4137 |
| $m^{avg}(s_1^{2*}) - m^{avg}(s_1^{1*})$ | **1.4757** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| $\|e_1 = 0$ | **2.5347** | $<2.2*10^{-16}$ | $5.13*10^{-16}$ |
| $\|e_1 = 2$ | **1.8403** | $8.02*10^{-10}$ | $2.52*10^{-9}$ |
| $\|e_1 = 4$ | **1.2153** | $1.07*10^{-5}$ | $1.44*10^{-5}$ |
| $\|e_1 = 6$ | **0.9375** | 0.0002 | 0.0003 |
| $\|e_1 = 8$ | **1.2500** | $1.28*10^{-5}$ | $1.71*10^{-5}$ |
| $\|e_1 = 10$ | **1.0764** | 0.0003 | 0.003 |

Table 5.7 Differences in the investments and mark-ups within a strategy and associated p-values (2 players)

| 3 players<br>$Z = 2$ | Absolute mean difference | Paired t-test | Wilcoxon test |
|---|---|---|---|
| $i^{avg}(s_1^{2*}) - i^{avg}(s_1^{1*})$ | 0.0251 | 0.0945 | 0.0937 |
| $\|e_1 = 0$ | 0.0595 | 0.0548 | 0.0546 |
| $\|e_1 = 2$ | 0.0258 | 0.4917 | 0.4968 |
| $\|e_1 = 4$ | 0.0694 | 0.0662 | 0.0659 |
| $\|e_1 = 6$ | 0.0119 | 0.7465 | 0.7454 |
| $\|e_1 = 8$ | -0.0198 | 0.6110 | 0.6126 |
| $\|e_1 = 10$ | 0.0040 | 0.9175 | 0.9172 |
| $m^{avg}(s_1^{2*}) - m^{avg}(s_1^{1*})$ | **0.6134** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| $\|e_1 = 0$ | **0.6448** | 0.0069 | 0.0065 |
| $\|e_1 = 2$ | **0.8929** | $1.58*10^{-5}$ | $5.90*10^{-7}$ |
| $\|e_1 = 4$ | **0.7540** | $1.88*10^{-5}$ | $1.99*10^{-6}$ |
| $\|e_1 = 6$ | **0.4464** | 0.0009 | 0.0005 |
| $\|e_1 = 8$ | **0.4167** | 0.0018 | 0.0010 |
| $\|e_1 = 10$ | **0.5258** | $9.89*10^{-6}$ | $5.19*10^{-6}$ |

Table 5.8 Differences in the investments and mark-ups within a strategy and associated p-values (3 players)

This means that a contractor believes that, on average, he will need to invest less in the second project than for the first project. Conditioning on the experience levels could not guarantee significant results for all the levels. Moving towards three shortlisted bidders, a small significance is attributed to the opposite finding, but for the majority of experience levels, neither the paired t-test, nor the Wilcoxon signed rank test proves significant *ex ante* differences. On the contrary, the mark-up dynamics are more outspoken. For both the two-player case as well as the three-player case, the optimal mark-up is expected to be set significantly higher for the second project than for the first project.

#### *5.4.2.2 First-project comparison*

More interestingly, Table 5.9 and Table 5.10 report the results of the scenario-specific differences between the preferred pre-tender investment level and the mark-up level for the first project in the two-project environment and the single-project environment respectively. The average results over all scenarios are highly significant for the mark-up. The mark-ups of the first project considerably drop when a second project is introduced in both the two- as well as the three-player situation, with an average decrease of 2.40% and 1.05% respectively. For both cases, the absolute impact is greater for inexperienced players than for more experienced ones.

With respect to the investment levels, the statistical tests confirm that pre-tender investments ought to be higher when a second project is added to the pipeline in the two-player setting. For the three-player case, no significant overall impact could be shown, but inexperienced players will now invest less than when the government has no project agenda. According to the ANOVA results that prove significance for the interaction between $e_1$ and the vector $e_{-1}$ (see Appendix C for a full overview), it is in the subgames in which the player has a competitive disadvantage that he refrains from investing more.

A final point of interest relates to the division of the efforts over the projects in the pipeline (i.e., whether there is a greater average investment in the overall pipeline). Nevertheless, a comparison of the results of the average investment percentage and mark-up percentage with the choices in the case that there is no pipeline did only support the mark-up drop (that amounts to -1.7% in the two-player case and -0.7% in the three-player case), while the average investment over the pipeline is only significantly higher for the two-player case (+0.1%). The average pay-off expectation per project drops with € 5,137 in the two-player environment and with € 2,221 in the three-player case according to the simulation.

| 2 players<br>Measured difference<br>w.r.t. $Z = 1$ | | Absolute mean difference | Paired t-test | Wilcoxon test |
|---|---|---|---|---|
| Investment | All scenarios | **0.1585** | $3.76*10^{-8}$ | $4.35*10^{-8}$ |
| | $e_1 = 0$ | **0.3194** | $8.57*10^{-6}$ | $1.16*10^{-5}$ |
| | $e_1 = 2$ | **0.2222** | 0.0011 | 0.0012 |
| | $e_1 = 4$ | 0.0347 | 0.6125 | 0.6122 |
| | $e_1 = 6$ | **0.2153** | 0.0037 | 0.0039 |
| | $e_1 = 8$ | 0.0278 | 0.6956 | 0.6952 |
| | $e_1 = 10$ | 0.1319 | 0.0586 | 0.0596 |
| Mark-up | All scenarios | **-2.4016** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| | $e_1 = 0$ | **-3.5069** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| | $e_1 = 2$ | **-2.3958** | $<2.2*10^{-16}$ | $6.88*10^{-16}$ |
| | $e_1 = 4$ | **-2.3264** | $2.10*10^{-15}$ | $4.87*10^{-14}$ |
| | $e_1 = 6$ | **-2.2222** | $1.31*10^{-14}$ | $2.17*10^{-13}$ |
| | $e_1 = 8$ | **-2.2917** | $9.29*10^{-15}$ | $1.63*10^{-13}$ |
| | $e_1 = 10$ | **-1.6667** | $3.93*10^{-8}$ | $8.16*10^{-8}$ |

Table 5.9 Differences between the investment and mark-up choice for the first project of a two-project pipeline and the choices in a single-project environment (2 players)

| 3 players<br>Measured difference<br>w.r.t. $Z = 1$ | | Absolute mean difference | Paired t-test | Wilcoxon test |
|---|---|---|---|---|
| Investment | All scenarios | -0.0073 | 0.6178 | 0.6013 |
| | $e_1 = 0$ | **-0.1012** | 0.0018 | 0.0018 |
| | $e_1 = 2$ | **-0.0893** | 0.0181 | 0.0184 |
| | $e_1 = 4$ | -0.0079 | 0.8210 | 0.8078 |
| | $e_1 = 6$ | 0.0060 | 0.8687 | 0.8738 |
| | $e_1 = 8$ | **0.1052** | 0.0047 | 0.0049 |
| | $e_1 = 10$ | 0.0437 | 0.2189 | 0.2215 |
| Mark-up | All scenarios | **-1.0516** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| | $e_1 = 0$ | **-1.3988** | $9.89*10^{-8}$ | $1.10*10^{-7}$ |
| | $e_1 = 2$ | **-1.2401** | $1.91*10^{-7}$ | $3.16*10^{-9}$ |
| | $e_1 = 4$ | **-1.0417** | $4.87*10^{-9}$ | $1.01*10^{-10}$ |
| | $e_1 = 6$ | **-0.9722** | $3.97*10^{-12}$ | $5.19*10^{-13}$ |
| | $e_1 = 8$ | **-0.7440** | $7.53*10^{-9}$ | $4.66*10^{-10}$ |
| | $e_1 = 10$ | **-0.9127** | $1.88*10^{-15}$ | $7.46*10^{-16}$ |

Table 5.10 Differences between the investment and mark-up choice for the first project of a two-project pipeline and the choices in a single-project environment (3 players)

The ANOVA output in Appendix C reveals the sensitivity results of the scenario-defining parameters and also underline the heterogeneous responses in a two-player or a three-player setting. From these ANOVA results, it also seems noteworthy to look into the project complexity parameters and the government reimbursement parameter.

### *5.4.2.3 Project complexity*

Figure 5.2 digs into the project complexity in the two-player setting. Omitting interaction effects, projects with a limited complexity and that do not require a lot of research ($\gamma_i$=0.05) incur a significant increase of 0.25% ($p=9.6*10^{-6}$) in the investment willingness. The increase in investment willingness drops to 0.18% ($p=2.6*10^{-4}$) when the share of the variance that is related to investment rises to 0.10. In the cases for which $\gamma_i$ reaches 0.20, the investment willingness is not significantly influenced by one additional project. In the two-player case, the mark-up results are also significantly related to the project's complexity. The average mark-up drops for the risk categories with $\gamma_i$ equal to 0.05, 0.10 and 0.20 are 0.89% ($p=2.29*10^{-12}$), 2.26% ($p<2.2*10^{-16}$) and 4.06% ($p<2.2*10^{-16}$) respectively. Thus, mark-ups for project categories with larger risk features drop more, ceteris paribus. Interestingly, Figure 5.2 shows that the mark-up for the first project has become increasing in the experience level in the two-project setting, while it was relatively stable in the single-project setting. Especially for complex projects, experienced players require higher mark-ups than their inexperienced counterparts.

This differs from the three-player setting of Figure 5.3 in which the downward mark-up trend for increasing experience levels remains. When the impact of the knowledge parameter $\gamma_i$ is studied in a three-player environment, little significance is found for the investments. In the high-risk setting ($\gamma_i = 0.2$), the introduction of an extra project results in a drop (0.09% on average with p-value 0.0012) of the investment willingness and no significant drops in mark-ups are apparent.

However, for lower risk projects, the mark-up impact is largest ($p<2.2*10^{-16}$), especially for inexperienced players.

#### *5.4.2.4 Government compensation*

As the bidding behavior is rather levelled, the government compensation is not necessary to increase competition in the case where two bidders are shortlisted for a single project. Increasing the number of projects in the pipeline does not modify the dynamics. Also the ANOVA results (Appendix C) do not report significant (at the 5% level) main or interaction effects with the government compensation parameter.

As has already been highlighted in Section 5.4.1, in the three-player setting with one project, government compensations are a helpful tool to increase competition. The ANOVA study does support that the effect of government compensations is influenced by the introduction of a second project in the pipeline. While only a limited number of compensation levels has been tested, a 60% compensation will for instance result in a 0.06% higher investment level ($p=0.0429$) and a 1.32% lower mark-up ($p<2.2*10^{-16}$), relative to its respective single-project scenario. Consequently, ceteris paribus, the pipeline amplifies the effect of a government reimbursement in the three-player setting.

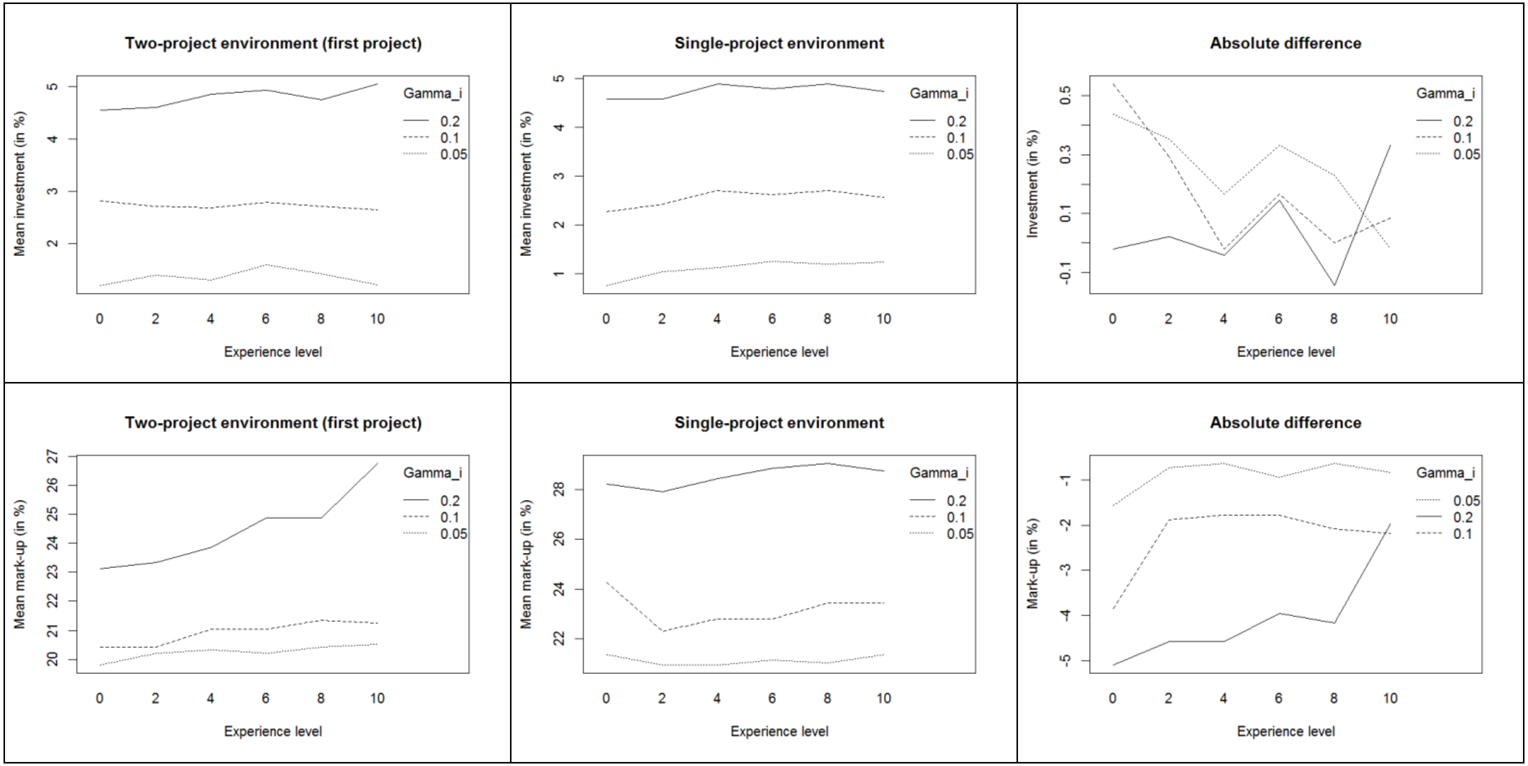

Figure 5.2 Interaction plots of project complexity and the experience level in the two-player setting with independent variable the choices for the first project in a two-project pipeline (left), the single-project strategy (middle) and their difference (right)

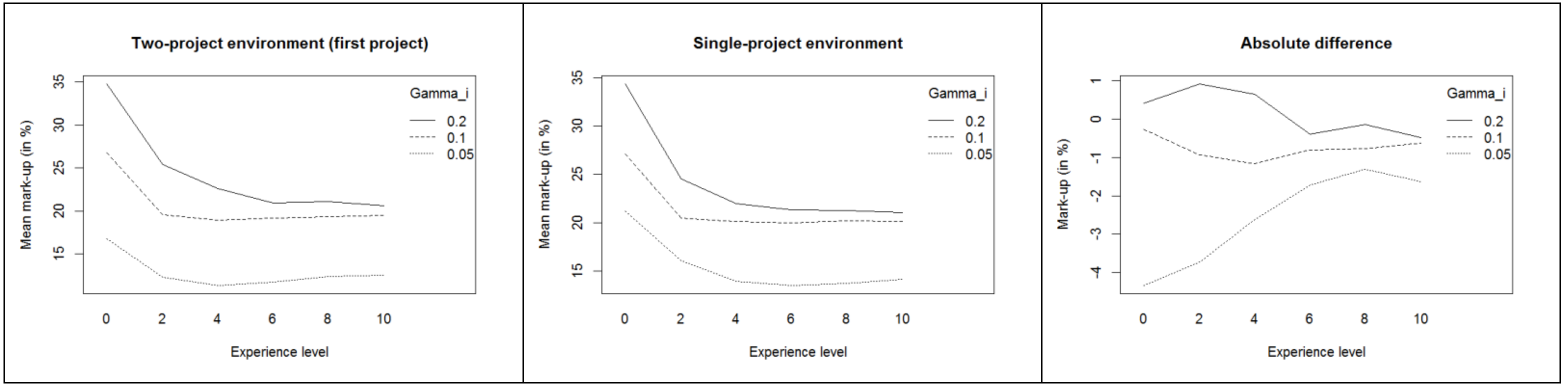

Figure 5.3 Interaction plots of project complexity and the experience level in the three-player setting with independent variable the mark-up choice for the first project in a two-project pipeline (left), the single-project strategy (middle) and their difference (right)

### 5.4.3 Hypotheses

As a summary, it is necessary to look how the hypotheses from Section 5.3.2 are backed up by the experimental findings. Unfortunately, the model could not provide a definite answer for Hypothesis 1. The VSM for the two-player case slightly supports the investment increase, but no investment change has been identified in the three-player case. There is an important interaction with the investment willingness and the competitive position in the market. However, all models support Hypothesis 2. A pipeline does have a beneficial impact on the mark-up, which also results in lower procurement costs for the government (Hypothesis 4). Last but not least, with respect to Hypothesis 3, markets become more competitive from a mark-up perspective when more projects are introduced, but it does not necessarily serve as a mechanism to level the playing field in a multi-player case. Therefore, government compensations could still help in three-player settings with complex projects to increase the competition.

## 5.5 Special topic: Spillover model

The previous sections of this chapter and also the sequential model of Chapter 6 do not account for the transferability of knowledge and efforts that result from research investments in past tenders. Both the current *ex ante* model as well as the sequential model only account for spillovers if the bidder has won a project. If a bidder wins a project earlier in the pipeline, he obtains an increase in the experience level for future tenders. However, the investments that have been performed were assumed to be project-specific so that investments could not be transferred to other projects. This addendum relaxes the non-transferability assumption and introduces a spillover variable $\alpha$. This variable reflects the fraction of the investment of the previous project that will have an impact on the cost and knowledge outcome of the next project. In that sense, the investment gets a propagation characteristic. Consider for instance a two-project setting and an *ex ante* strategy given by $s_1 = \left(i(s_1^1), m(s_1^1), i(s_1^2), m(s_1^2)\right) = (3\%, 10\%, 1\%, 15\%)$ and a spillover rate $a = 0.5$. Thus, the 3% investment of the first project still has an impact in the second tender. As a result, in order to calculate the variance and cost impact with equations (3.5) and (3.6) the value $i(\overline{s_1})$ in these equations is 3% in the first tender and 2.5% (=1%+0.5*3%) in the second tender.

In order to test the impact of the spillover capacity, a fraction of the scenarios from the VSM has been re-executed. The scenarios that have been tested are defined by the following parameter settings: $\gamma_i$ equal to 0.10 and 0.20, $\gamma_e$ equal to 0.05 and 0.10 and $d$ equal to 0, 0.30, 0.60 and 0.90. The other parameters are kept constant: $\beta_e = 0.1$, $\beta_i = 0.05$ and $\lambda_i = \lambda_e = \mu_i = \mu_e = 0.25$. The simulation experiment runs in the same fashion as described in the simulation model of Section 5.3.4 and the equilibrium approximation of Section 5.3.5. As expected, the introduction of this spillover parameter has significant consequences for the equilibria.

As in the previous analysis, we first look at the impact of this spillover parameter on the investment efforts of the first project of the two-project pipeline. Figure 5.4 plots the two-player results of the aggregate scenarios and Figure 5.5 concerns the three-player scenarios. The graphs indicate the increased investment efforts in both the two-player as well as the three-player context, regardless of the experience level of the player. According to the experiment, the mark-up does not seem to be influenced by the spillover rate at the first sight. Besides, the spillover rate does not close the gap between the investment and mark-up percentages of the inexperienced versus the experienced players.

Without spillovers, the comparison of the strategy in a single-project setting with the optimal investment and mark-up decision in the two-project setting did not always present significant differences. Since this section proves the dynamics of the equilibrium in case of a spillover effect, this could now result in significant conclusions. For the two-player scenarios, even a 10% spillover rate does already give a significant positive difference of 0.37% in the average investment for the first project compared to a situation in which only one project is tendered ($p=2.8*10^{-13}$). The same can be said for the three-player results. While the investment efforts were even decreasing in the case of a pipeline for inexperienced players, they now turn out to be already 0.24% greater ($p<2.2*10^{-16}$) in a world with spillover effects.

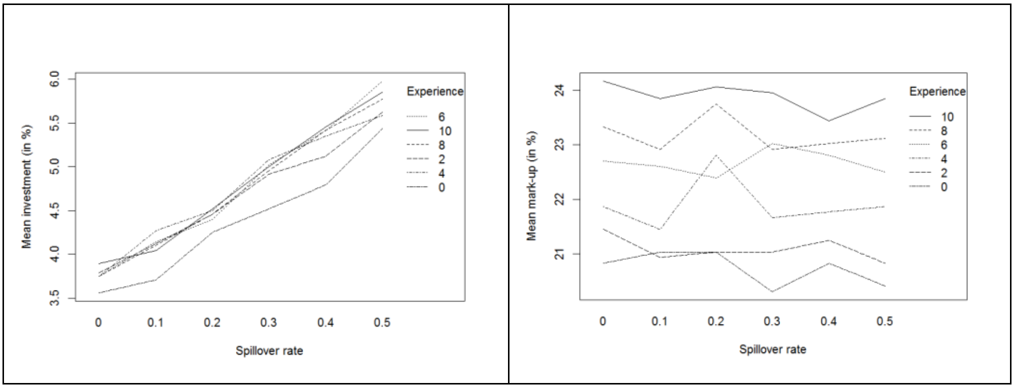


Figure 5.4 Impact of the spillover rate on the first-project investment decision in a two-project setting with two players

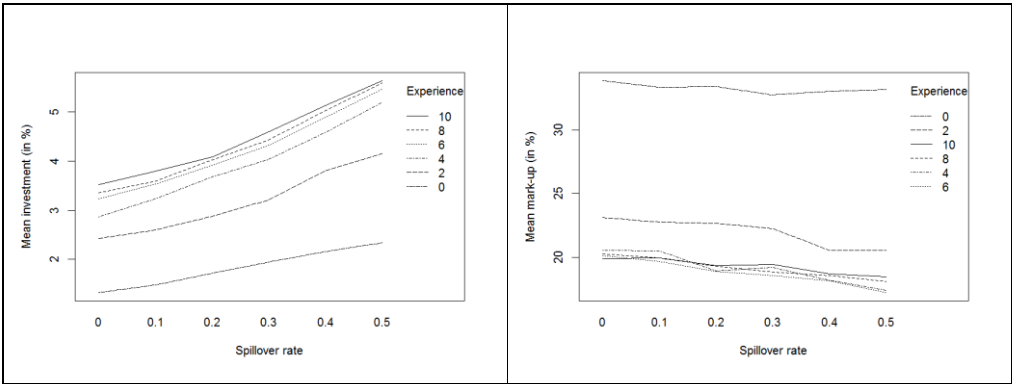


Figure 5.5 Impact of the spillover rate on the first-project investment decision in a two-project setting with three players

In the two-player scenarios that have been tested in this section, mark-ups for the first project in a two-project pipeline with $\alpha = 0$ are on average 3.58% lower ($p<2.2*10^{-16}$) than when only a single project is announced. An increase in $\alpha$ does not significantly modify this, which is slightly different in the three-player scenarios. While the mark-up drop is only 0.26% (p=0.0786) without spillovers, the drop becomes 0.53% when $\alpha = 0.1$ (p=0.0005) and to 2.39% when 50% of the investment outcomes are transferable ($p<2.2*10^{-16}$).

It is rather intuitive that the investment in early tenders would increase, but what happens if we look at the average investment and mark-up choices along the pipeline? In this exploratory experiment, the average investment in equilibrium of the first and the second project are compared to the respective single-project investment. In the two-player case, the average pipeline investment is found to be larger in a situation without spillovers (p=0.0387), but from a spillover rate of 30% onwards, the average investment is 0.11% lower than a situation in which neither spillovers nor a pipeline are present (p=0.0128). So the bidder mostly counts on his knowledge from the first project to study the second tender. In the three-player setting, this negative impact is already significant for spillover rates of 10% (p=0.0129).

Finally, it is necessary to verify how the dynamics are interrelated with other parameters. Nevertheless, the sign of the main effects of the spillover rate are not significantly influenced by the other parameters. However, some effects on the slope of the trend are noteworthy. In the two-player setting, we stated that overall, mark-ups do not considerably change in case of a spillover effect. Nonetheless, mark-ups do decrease in $\alpha$ for the scenarios with a low government reimbursement fraction ($d = 0$ or $d = 0.3$). And since reimbursements are not necessary in a two-player context, one might claim that the spillover effect will inflate investments and reduce mark-ups for the first project of a two-project pipeline. For the three-player case, the results pointed towards these overall decreasing mark-ups if the spillover rate surges. A more detailed look reveals that this is mostly attributed to the scenarios without government reimbursement. The findings related to the investments are robust for changes in the reimbursement level, ceteris paribus. For both the two-player as well as the three-player scenarios, the spillover impact is not interacting with the contingency parameters $\gamma_i$ and $\gamma_e$.

From this model extension, it is clear that the spillover rate significantly influences the bidding behavior of all players. Its impact is rather equivalent for any level of experience. As a consequence, experiential inequalities will not be levelled by the spillover rate. So, the three-player tenders might still benefit from investment cost reimbursements by the government. Evidently, the spillover does have important benefits: it will incentivize bidders to invest more in the early stages of the project pipeline and contractors can use past experience in future tenders, which might be more easily sellable to the management and the board when project opportunities are discussed. Therefore, the government should take part in developing efforts to increase the transferability of efforts, for instance by the standardization of contracts.

Admittedly, the shortcomings of the simulation methodology also need to be taken into account here. On the other hand, it is a daunting task to fully implement the spillover rate in the sequential structure of Chapter 6 that elaborates on the Markov perfect equilibrium outcome of the sequential stochastic bidding game. In that approach, the equilibrium strategy consists of state-dependent optimal actions that are only limitedly influenced by actions from the past. The spillover rate would incur that the (outcomes of the) actions are dependent on the actions that have been taken before, which would lead to a proliferation of states.

## 5.6 Conclusion

This chapter was the first attempt to extend the PPP bidding model towards a dynamic setting with a sequence of stochastically equivalent projects. More particularly, it assessed how contractors change their *ex ante* bidding strategy in the case a pipeline of projects is introduced. The tendering processes are time-consuming and often overlapping, so contractors will make an initial budget how to spread their bidding efforts over the different stages of the game, in the belief that experience of winning a project will benefit the competitive position in later tenders. The introduction of extra projects mainly has a mark-up impact and consequently reduces the expected government procurement cost. Consequently, from a government perspective and besides from cementing the project agenda, it might also be beneficial to split up large projects into smaller parts as long as there are no coordination issues. It is apparent that adding one project to the project renders the largest mark-up drop. Consequently, cementing a trustworthy, short-term pipeline is beneficial.

The model could not support the hypothesis that all contractors will put more effort in the bid preparation. Looking at the heterogeneous bidding settings, the players with a competitive advantage are incentivized towards additional investments efforts. Instead, contractors take the expected profits of an experiential gain into account for the *ex ante* strategy determination and therefore directly increase the probability of winning by decreasing the mark-up for initial projects. Especially in three- and four-player markets, appropriate incentives are necessary to assure competitive forces. In this way, they prevent the market to become saturated or the mature players to become too comfortable with their competitive advantage. Therefore, governments should first try to reduce bidding costs that add no value, like excessive design requirements or lengthy negotiation processes. Additionally, the spillover study proves that investment efforts in early projects grow in the case the knowledge and project cost savings from the investment efforts propagate in future tenders. In case governments want to benefit from this insight, they should strive for standardization of the tendering procedures and documents.

Contractors should also ensure that the investment efforts they undertake are easily transferable to future tenders. This strengthens the competitive position and mitigates the risk for the current project, but also allows to take a lead in future tenders. Furthermore, it is worthwhile to take the future pipeline into account when one wants to enter a PPP market. Fiercer competition is required, but risks are more spread out over different projects.

The *ex ante* model of this chapter is an extreme case that does not allow to modify strategies when new information becomes available. Chapter 6 points in the (extreme) opposite direction in which contractors choose optimal actions with respect to the state of the game.

# Chapter 6 Sequential procurement model

## 6.1 Introduction

This chapter relates to the public-private partnership pipeline of Chapter 5. In order to ensure competition, policy makers are endowed to seek for feasible ways to substantiate the PPP market's attractiveness. A project pipeline could bring solace. In Section 5.1, a PPP project pipeline has been defined as:

*A PPP project pipeline is a sequence of similar projects that the government ensures to tender in the near future. It may concern totally independent projects or sub-projects that serve a larger purpose.*

Past PPP experiences have led to concise lists of success factors and key performance indicators (e.g., Jefferies 2006, Yuan et al. 2012[b]). Nevertheless, the majority of the studies are limited to attaining single-project success without looking at the broader PPP picture. However, empirical results also underline long-term and country-specific factors like the country's government reputation, legal framework and economic stability (e.g., Aziz 2007[b], Chan et al. 2010[a], Yuan et al. 2012[b]) or the importance of PPP units in promoting PPPs (Tserng et al. 2012).

While the previous chapter aimed for developing an *ex ante* strategy for a set of projects with overlapping procurement stages, this chapter considers a fully sequential model. The sequential setting allows for changing the strategy along the pipeline, which means that tenders are strictly sequential and at each point in time (i.e., at each stage in the game), there is perfect information on who has won or lost the previous tenders. The sequential model thus introduces the concept of a *state* of the game that consists of a particular experience vector together with the number of projects that remain in the sequence. Equivalent to the philosophy from the *ex ante* model, winning a contract increases the experience in future tenders both from a knowledge perspective as well as from an efficiency or cost perspective.

The subsequent sections analytically characterize the structure of the stochastic game and employ an experimental setting to approximate the Markov perfect equilibrium for different project cost features and a varying number of projects in the pipeline. The method of Section 6.3.4 applies a best response heuristic for which an algorithmic approximation that is based on both an electromagnetism-like mechanism as well as a local search procedure detects the best response. This approach guarantees to look at the entire, continuous action search space in order to identify candidate equilibria.

The contribution of this chapter adds to the discussion of the possible usefulness of a project pipeline that commenced with the *ex ante* model of Chapter 5. In reality, PPP tendering procedures are neither always overlapping, nor is it always possible to modify your strategy for each project. Nonetheless, the combination of the results of both extreme situations guide towards trustworthy conclusions for the field. From a methodological perspective, this chapter follows an entirely different approach. Instead of approximating a contractor's best equilibrium response, this chapter draws back to a Nash equilibrium approach, conceptually comparable to the Nash equilibrium algorithm of Section 4.3.3.1. In this vein, this chapter allows to create an overall view on the equilibrium instead of focusing on a single player. An important result in Section 6.4.4 serves as an example of the contribution of this particular approach. Besides, the method that is presented does not require a discretization of strategies, but allows for a continuous spectrum of investment and mark-up percentages. And last but not least, while a multi-agent simulation approach derives the expected pay-offs in Chapter 4 and Chapter 5, the contractors' pay-offs are exactly computed for presumed distributions in this chapter.

In a managerial vein, the sequential model confirms the idea that a pipeline could reduce the average project procurement cost due to increased pricing competition. However, the model outcome differs from the practitioner's perception in the sense that it only delivers support for increased investment efforts by consortia that have obtained a competitive advantage. Ultimately, the chapter suggests that governments could benefit from a combination of bid cost reimbursements that levy the investment barrier and a pipeline that reduces the project cost and that partially offsets the additional reimbursement expenditures.

## 6.2 Literature review

Albeit analytically-driven, the sequential auction literature is perhaps the most closely related to the study of the PPP pipeline. The literature review of Section 5.2 gives an overview of the dimensions on which the sequential or multi-unit auction literature can be positioned. The PPP model of this dissertation adds an important feature into the discussion: the pre-tender investment decision. Besides a mark-up, contractors in a PPP tender make a decision on the pre-tender research efforts, but to the best of our knowledge, there have been no previous studies on the impact of a sequential mechanism on the willingness for information acquisition. The work of for instance Persico (2000), Bergemann and Välimäki (2002) and Shi (2012) considers a single-shot game in which the bidders can gain information on the value of the auctioned object, but they do not extrapolate to a multi-unit environment.

With respect to the sequential bidding literature, this chapter is closely related to the contribution of Takano et al. (2014) who study the competitive bidding strategy in a sequential setting with inaccurate cost estimates. Building upon earlier research from Naert and Weverberg (1978) and King and Mercer (1990), the authors explicitly account for the fact that bids are usually correlated with the estimated cost that is subject to inaccuracies. Takano et al. (2014) apply a scenario-based approach for the cost estimates and a capacity constraint. Our work differs from and extends this study in several aspects. First of all, in addition to the mark-up choice, a bidder makes an investment decision that reduces the uncertainty and the expected cost. Secondly, Takano et al. (2014) simulate costs and bids for the competitors, while we look at action equilibria by simultaneously optimizing each bidders' pay-off. Thirdly, our model does not include capacity constraints or a value at risk constraint and deals with a constant number of heterogeneous contractors.

Since the most prominent literature on sequential auctions has been discussed in the previous chapter, the remainder of this section considers the related literature from a methodological perspective. The methodological approach is based on a dynamic programming model for which Markov equilibria are approximated based on a best response heuristic. The Markov perfect equilibrium concept, drawn from the study of Maskin and Tirole (2001), is a solution concept that solves the stochastic game with a finite number of stages and in which the pay-off and probabilistic transitions depend on the current state and the chosen actions (Shapley 1953). The solution concept is not uncommon within the auction literature. In a sequential auction setting with randomly arriving bidders, Said (2011) derives Markov equilibria to discuss bid shading (i.e., placing a bid below the estimated value) as a consequence of an option value of participation in future auctions. Within a procurement setting, Katehakis and Puranam (2012) study the cost minimization objective of a buyer who wants to procure a fixed number of products and Yildirim (2004) considers the optimal mechanism for piecewise procurement of large-scale projects. While these studies (and our work) do not account for capacity constraints, Jofre-Bonet and Pesendorfer (2003) include capacity limitations when defining the states of the game and they use empirical highway procurement bidding data to develop an estimation method for a repeated auction. Whereas most models allow for a different number of bidders in each stage, the PPP model assumes repeated competition among a consistent set of bidders (like in Milgrom and Weber (1982[a]) and Harstad (2010)) and includes the current levels of the bidders' past experience and the number of projects remaining in the state variable. Hence, the PPP model allows for heterogeneity among the bidders. Moreover, in contrast to models that study infinite time frames (e.g., Oren and Rothkopf 1975, Hörner and Jamison 2008, Zeithammer 2007) the PPP pipeline has a finite nature which is a logical consequence of the magnitude of the projects and the limited budget horizon of governments.

The experimental setup relies on a heuristic approach to derive the equilibrium. Algorithmic game theory attempts to deal with the complexity of real-life models (Nisan et al. 2007). Algorithms that use best response reasoning have been successfully implemented for instance in empirical games, routing games or dynamic oligopoly models and often limit the search space and the number of computationally expensive pay-off calculations (e.g., Sureka and Wurman 2005, Vorobeychik and Wellman 2008, Farias et al. 2012). Nevertheless, a best response heuristic does not always converge and, to the best of our knowledge, formal proofs of convergence are limited to super-modular games with unique Nash equilibria (Milgrom and Roberts 1990) and congestion games (Monderer and Shapley 1996). The experimental results in this paper focus on the scenarios for which convergence has occurred, which was the case in the majority of scenarios.

## 6.3 Methodology

This chapter extends the single-project model of Chapter 4 towards a setting with $Z$ consecutive projects. Nevertheless, there is an important difference with the multi-project setting of Chapter 5 in which an *ex ante* strategy has been defined. This chapter assumes that all projects are strictly sequential and that at each point in time (or at each stage of the game), the contractors exactly know their competitive position. Since, the methodological approach is considerably different in this chapter, some new notation, drawn from the sequential auction literature, is introduced in the subsequent sections in order to avoid confusion.

### 6.3.1 Competitive bidding procedure

The structure of the competitive bidding procedure is essentially the same as before. In a particular stage $z$ of the game, contractors that are invited for the tender will first determine how much effort they are willing to put into the bid preparation. This investment may result in a reduction of the cost uncertainty as well as in a cost advantage. Moreover, the heterogeneity among contractors leads to more advantageous cost probability distribution functions for more experienced players, which means a smaller variance and a lower average expected cost. After the investment decision, each contractor $p$ estimates the project cost that is inherently subject to estimation errors. Moreover, the mark-up is determined and applied to the estimated cost, resulting in the bid for project $z$. The lowest bidding contractor is granted the project. Afterwards, the tendering procedure for stage $z+1$ is initiated. The sequential model adds an additional feature: winning a project in the sequence results in additional experience for all subsequent projects.

### 6.3.2 A sequential bidding model

Given is a commonly known project sequence $\mathcal{Z} \coloneqq \{1,2,\dots,Z\}$. We want to identify the strategy equilibrium of the subgame $e = (e_1, e_2, \dots, e_P)$ that defines the initial experience setting of the players of the game. The experience levels are defined on the experience-scale [0,10] with a user-defined number of experience intervals $e_u$. This setting is a *stochastic game*, as has been introduced by Shapley (1953). A stochastic game is a finite or infinite dynamic game that is played by one or more players with probabilistic transitions between a finite number of states. In this setting, the players are assumed to be long-lived and to have unlimited capacity to perform all the projects of the pipeline. In each stage of the sequential game, the contractors want to optimize their expected pay-off which consists of the instantaneous pay-off of the current stage and an expected continuation value of the pay-offs in future stages. In order to limit the number of strategies that needs to be considered, we are looking at Markov strategies and identify a Markov perfect equilibrium (MPE) as presented by Maskin and Tirole (2001). The MPE is a refinement approach in game theoretic settings and is a special version of the notion of subgame perfectness. The use of the MPE is justified as the current play is only influenced by the expected pay-offs of future projects on the one hand and the state variable on the other hand. In other terms, the current actions are only limitedly influenced by actions from earlier tenders, namely only by the fact whether you won or lost the previous tender(s). But before moving to the equilibrium determination of Section 6.3.4, this section explains the generic structure of the different elements of the total expected pay-off, while Section 6.3.3 elaborates on the specific implementation for the dissertation's PPP setting.

The concepts *stage*, *state* and *action* are essential to guarantee a fluent understanding. Figure 6.1 gives an example of an (optimal) sequential strategy and serves as a guidance to worm your way through the notation. The figure's notation uses an asterisk with the actions to indicate that the reported strategy is optimal in this example. A stage, introduced in the previous chapter, refers to which project of the sequence is tendered. For a given stage $z \in \mathcal{Z}$ from the sequence, we determine the current state $\theta^z \in \Theta^z$ as the combination of the current experience levels and the number of remaining projects in the sequence $Z - z$ or $\theta^z = (e, Z - z) = (e_1, e_2, \dots, e_P, Z - z)$. The history $h_z$ at stage $z$, that consists of the information on what has happened earlier in the stochastic game, is summarized into this state variable $\theta^z$ and $\Theta^z$ is the set of all possible states that could occur in stage $z$. Consequently, we assume that past investment and mark-up decisions, the so-called past actions, solely impact the current behavior by having won or lost the past tender. For a given state $\theta^z$, a set of actions $\mathcal{A}_p^z = \mathcal{A}_p^z(\theta^z)$ is available for each player. We assume that the set of available actions is the same in every state of the game, so that we can refer to the set of actions as $\mathcal{A}_p$. An action $a_p^z \in \mathcal{A}_p$ in a given state $\theta^z$ is composed of two elements: the amount of pre-tender investment $i(a_p^z|\theta^z)$ a player $p$ is willing to adopt and which is expressed as a percentage of an initial cost base equal to 1 and the mark-up $m(a_p^z|\theta^z)$ defined as a percentage that is applied to the estimated project cost. The vector $a^z = (a_1^z, \dots, a_P^z)$

represents the action profile or the combination of actions (i.e., the investment and mark-up percentages) for all $P$ players. If we define the set of players as $\mathcal{P}$ and the set of action profiles as $\mathcal{A} = \times_{p \in \mathcal{P}} \mathcal{A}_p$, then we determine the transition probabilities $Q$ from $\mathcal{A} \times \Theta^z$ to $\Theta^{z+1}$ so that $Q(\theta^{z+1}|a^z, \theta^z)$ represents the probability of arriving in state $\theta^{z+1}$ from the current state $\theta^z$ with an action profile $a^z$. For each stage $z$, the vector $\pi^z(a^z|\theta^z)$ of dimension $\mathbb{R}^P$ represents the total expected pay-off for each of the players, with $\theta^z$ the given state vector in this node of the stochastic game and $a^z$ the decision variables or the action profile of the players. Each player-specific element $\pi_p^z(a^z|\theta^z)$ of this vector is the sum of an instantaneous pay-off $\rho_p^z(a^z|\theta^z)$ and the player's expected value $\mathcal{V}_p^{z+1}(a^z|\theta^z)$ for the future stages $\{z+1, \dots, Z\}$ discounted with a factor $\delta$ $(0 < \delta \leq 1)$. This continuation value depends on the actions that are taken at the current state, because these actions will determine the probability of arriving in each of the states in stage $z+1$. These probabilities are represented by the transition matrix $Q$ that represents, for a given action profile $a^z$ and a given state $\theta^z$, the probabilities of arriving in all states $\theta^{z+1}$. In summary, the player-specific total expected pay-off function that player $p$ wants to optimize at stage $z$ equals:

$$\pi_p^z(a^z|\theta^z) = \rho_p^z(a^z|\theta^z) + \delta \mathcal{V}_p^{z+1}(a^z|\theta^z) \tag{6.1}$$

with

$$\mathcal{V}_p^{z+1}(a^z|\theta^z) = \sum_{\theta^{z+1} \in \Theta^{z+1}} Q(\theta^{z+1}|a^z, \theta^z) \pi_p^{z+1}(a^{z+1}|\theta^{z+1}) \tag{6.2}$$

and for each $z \in \mathcal{Z}$ and $\theta^z \in \Theta^z$. Furthermore, we assume that the continuation value of the final project of the pipeline is zero, or $\mathcal{V}_p^{Z+1}(a^Z|\theta^Z) = 0$ for all $p$. Hence, the total expected pay-off is a linear combination of instantaneous pay-offs. Before moving on to the characterization of the equilibrium, the instantaneous pay-off for the PPP model needs to be determined.

A *strategy* maps the actions for all the possible states of the game. Hence, the combination of investment and mark-up outcomes in Figure 6.1 represent an example of an equilibrium strategy profile, while the particular pattern for a single player represents the optimal strategy in equilibrium.

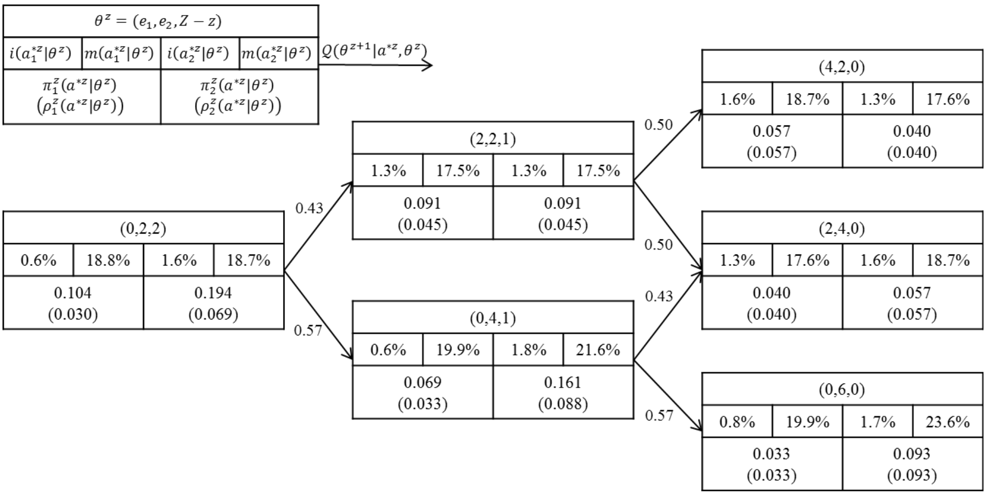


Figure 6.1 Example of the sequential strategy for two players and three projects with $e_u = 5$ and the parameters according to Sc. 1

The figure represents a three-project pipeline. Given is also that the experience scale is divided into $e_u = 5$ intervals. In the case of an experience scale [0,10], the six experience levels are {0,2,4,6,8,10}. The initial experience levels of the two players are 0 and 2 and there are two projects remaining, so the state is defined as (0,2,2). There are two possible outcomes for the first project: player 1 wins and he moves to experience level 2 or player 2 wins and obtains experience level 4. Therefore, the second stage of the pipeline has two states (2,2,1) and (0,4,1). Looking at the equilibrium, player 1 invests 0.6% and requests a mark-up of 18.8% for the first project. If player 1 wins, which happens with a probability of 43% in equilibrium, he or she invests 1.3% and requests a mark-up of 17.5% in the second stage. Alternatively, if player 2 wins the first stage, player 1 invests 0.6% with a mark-up of 19.9% in the second stage.

### 6.3.3 Expected pay-off calculation in the PPP model

While the assumptions of the previous studies remain valid, we prefer to repeat the main elements for the convenience of easily implementing the notational modifications. First of all, it is assumed that the state of the game, which consists of the experience levels and the remaining projects in the pipeline, is common knowledge to all players. Moreover, the general risk structure of the projects is the same for all the projects in the pipeline. That means that, without considering experience and pre-tender investment, the *ex ante* cost probability distribution and its parameters do not change.

The experience and the current investment level may change the shape of the cost probability distribution. The model does not consider spillovers effects (in the sense of Section 5.5), so that the project-specific investments only directly affect the current stage and do not contribute to the knowledge base of future stages. With respect to the user-defined experience scale $[0{,}10]$, $e_u$ could refer to the number of projects won beyond which no extra experience can be adopted. Nevertheless, this does not need to be true, as experience may also entail other qualitative aspects like the consortium's reputation or the familiarity with a particular market or a specific project type. As before, the impact of experience and investment is implemented with diminishing scale effects and moreover, Gaussian distributions are assumed. Consequently[2], the contractor-specific project cost probability distribution $c_p^z\left(a_p^z|\theta^z\right)$ is of the form $N\left(1+g_p\left(a_p^z|\theta^z\right),\sigma_p^2\left(a_p^z|\theta^z\right)\right)$. We assume that $g_p(.)$ represents the fraction of the cost that is accountable for the lack of experience or investment and apply equation (3.6) as:

[2] Note that this is somewhat different from the implementation in Section 4.3.2 and Section 5.3.4 as at the time of studying this problem, we decided not to start from a common cost base distribution from which a cost base was randomly selected, but immediately relate the contractor-specific cost probability distribution to the investment efforts and the experience. Moreover, in line with the literature dealing with MPE in sequential auctions, we set the scaling factor $\mu$ equal to 1.

$$g_p\left(a_p^z|\,\theta^z\right) = \beta_i e^{-\mu_i\left(100i\left(a_p^z|\theta^z\right)\right)} + \beta_e e^{-\mu_e e_p(\theta^z)} \tag{6.3}$$

Moreover, the variance of the distribution is dependent on the experience level and the investment. The total variance of the cost probability density is composed of an uncontrollable part that is equivalent for all players, a part attributed to the (lack of) experience and a fraction related to the (lack of) investment. In this chapter's notation, we get:

$$\sigma_p^2\left(a_p^z|\theta^z\right) = \sigma^2 + \left(\gamma_i e^{-\lambda_i\left(100i\left(a_p^z|\theta^z\right)\right)}\right)^2 + \left(\gamma_e e^{-\lambda_e e_p(\theta^z)}\right)^2 \tag{6.4}$$

$\left(1 + g_p(.)\right)$ is the actual cost if player $p$ wins the bid. However, the player does not know this yet at the time of bidding. Instead, he receives a signal which is a cost generated from $c_p\left(a_p^z\middle|\theta^z\right)$. In order to account for the inaccuracy of this signal, the bidder sets a mark-up $m(a_p^z|\theta^z)$ that represents the risk premium and the profit margin.

As an example, assume that $e_u = 2$, $\sigma = 0.05$, $\gamma_i = \gamma_e = \beta_i = \beta_e = 0.1$, $\lambda_e = \mu_e = \lambda_i = \mu_i = 0.25$, then a player without experience, the first level on the scale, and a 1% investment choice has a cost probability distributed as $N(1.17788{,}0.01856)$ and for a player with experience level 5, the second level on the scale, and a 2% investment choice, we get $N(1.08930{,}0.00699)$.

When a contractor $p$ estimates the project cost $\widetilde{E_p^z}$, which is generated from the cost probability density $c_p^z(.)$, he applies a mark-up to the expected cost to arrive at the bid $\left(1 + m\left(a_p^z\middle|\theta^z\right)\right)\widetilde{E_p^z}$. Consequently, the bid probability distribution given a player's action $a_p^z$ and a state $\theta^z$ equals $b_p^z\left(a_p^z\middle|\theta^z\right)$ and is characterized by the normal distribution:

$$N\left(\left(1 + m\left(a_p^z\middle|\theta^z\right)\right)\left(1 + g_p\left(a_p^z|\theta^z\right)\right), \left(1 + m\left(a_p^z\middle|\theta^z\right)\right)^2 \sigma_p^2\left(a_p^z\middle|\theta^z\right)\right) \tag{6.5}$$

with the associated cumulative bid probability distribution $B_p^z$. If the lowest bidding contractor is granted the project, the probability of winning contract $z$ with $P$ players is, apart from notational adjustments, equivalent to equation (3.2): $q_p^z(a^z|\theta^z) = \int_{-\infty}^{+\infty} b_p^z(x_p)\left[\prod_{k\in\mathcal{P}\setminus\{p\}}\left(1 - B_k^z(x_k)\right)\right]dx_p$. These probabilities also refer to the transition probabilities $Q(\theta^{z+1}|a^z,\theta^z)$ to move from a state $\theta^z$ to $\theta^{z+1}$. The contractor that wins the project receives the proposed bid and pays the actual cost $\left(1 + g_p(.)\right)$ of the project together with the monetary investment effort. Additionally, this player obtains an updated experience level in all future stages of the game, until he reaches maximum experience. The pay-off of the other contractors is determined by the lost investment, but we account again for the fact that the government might reimburse losing bidders for the investment efforts with a fraction $d$. Consequently, the instantaneous expected pay-off (equivalent to equation (3.3)) for a player $p$ in an action profile $a^z$ and state $\theta^z$ is given by:

$$\rho_p^z(a^z|\theta_z) = q_p^z(a^z|\theta^z)\left(E\left[\widetilde{B_p^z}\middle|p \text{ has won}\right] - \left(1 + g_p\left(a_p^z|\theta^z\right)\right) - i\left(a_p^z|\theta^z\right)\right) - \left(1 - q_p^z(a^z|\theta^z)\right)(1-d)i\left(a_p^z\middle|\theta^z\right) \tag{6.6}$$

with the ex post expected proposal conditional on winning $E[\widetilde{B_p^z}|p \text{ has won}]$ equal to: $E\left[\widetilde{B_p^z}\middle|\widetilde{B_p^z} < \widetilde{B_k^z}, \forall k \neq p\right] = \int_{-\infty}^{+\infty} \frac{x_p}{q_p^z} b_p^z(x_p) \prod_{k\in\mathcal{P}\setminus\{p\}}\left(1 - B_k^z(x_p)\right) dx_p$. In order to arrive at the total expected pay-off for this state, the discounted player's instantaneous pay-offs of the future stages need to be added to the expected instantaneous pay-off.

### 6.3.4 Equilibrium identification

In order to find the Markov perfect equilibrium, one needs to identify the equilibrium action profile (i.e., each player's equilibrium investment and mark-up percentage) in each state. In every state, all players simultaneously optimize the total expected pay-off function (equation (6.1)). A player's pay-off is dependent on the actions taken by the opponents, so we need to propose the conditions for the action equilibrium. The equilibrium for this stochastic game is derived by backward induction. Consequently, in each state, it is assumed that the players bid according to the equilibrium in subsequent stages. In the stochastic game with $Z$ projects, the first order conditions for optimality in the last project (i.e., project $Z$) are defined as:

$\forall p \in \mathcal{P}, \forall \theta^Z \in \Theta^Z$:

$$\begin{cases} \frac{\partial \rho_p^Z(a^{Z*}|\theta^Z)}{\partial i(a_p^{Z*}|\theta^Z)} = 0 \\ \frac{\partial \rho_p^Z(a^{Z*}\,|\theta^Z)}{\partial m(a_p^{Z*}|\theta^Z)} = 0 \end{cases} \tag{6.7}$$

With this information on the action equilibrium in stage $Z$, the action equilibrium of stage $z = Z - 1$ can be derived and as soon as $z = 0$, a strategy equilibrium for the sequential game has been derived. The first order conditions in all states $\theta^z$ with $z \in \{1, \dots, Z - 1\}$ are:

$\forall p \in \mathcal{P}, \forall \theta^z \in \Theta^z, z \in \mathcal{Z}\backslash\{Z\}$:

$$\begin{cases} \frac{\partial \rho_p^z(a^{z*}|\theta^z)}{\partial i(a_p^{z*}|\theta^Z)} + \delta \sum_{k=1}^{P} \frac{\partial q_k^z(a^{z*}|\theta^z)}{\partial i(a_p^{z*}|\theta^Z)} \pi_p^{z+1}(a^{z+1*}|\theta^{z+1}, k \text{ wins}) = 0 \\ \frac{\partial \rho_p^z(a^{z*}\,|\theta^z)}{\partial m(a_p^{z*}|\theta^Z)} + \delta \sum_{k=1}^{P} \frac{\partial q_k^z(a^{z*}|\theta^z)}{\partial m(a_p^{z*}|\theta^Z)} \pi_p^{z+1}(a^{z+1*}|\theta^{z+1}, k \text{ wins}) = 0 \end{cases} \tag{6.8}$$

Since the derivative may not account for the border points of the investment and mark-up interval, one could also rely on the general definition for a Nash equilibrium in each state which states that none of the bidders has an incentive to deviate from his current action $a_p^{z*}$, given the action profile $a_{-p}^{z*}$, which is defined as the action profile of the opponents of player $p$:

$\forall p \in \mathcal{P}, \forall \theta^z \in \Theta^z, \forall z \in \mathcal{Z}, \forall a_p^z \in \mathcal{A}_p$:

$$\pi_p\left(a_p^{z*}\middle|\theta^z, a_{-p}^{z*}\right) \geq \pi_p(a_p^z|\theta^z, a_{-p}^{z*}) \tag{6.9}$$

Finding this equilibrium is a hard problem and a heuristic approach is developed. The equilibrium of the dynamic programming problem is first determined for the states that are related to the final project in the pipeline. This is appropriate since the current play is only influenced by the current state and not by other actions from an earlier stage. Based on a backward induction reasoning, the equilibria for each stage $z$ are determined, assuming equilibrium play in the stages $\{z+1, \dots, Z\}$. So for a state variable $\theta^z = (e_1, e_2, \dots, e_P, Z-z)$ that is composed of the experience levels of all players and the number of remaining projects in the pipeline, we want to derive an equilibrium action profile $a^* = (i_1, m_1, \dots, i_P, m_P)$[3], which is a vector with dimension $\mathbb{R}^{2P}$. If no confusion is possible, subscripts and superscripts related to the state variable are omitted so as to avoid notational complexity.

In order to determine the equilibrium, a straightforward best response heuristic is applied. In each iteration of the heuristic, the algorithm approaches the best response for each player sequentially, given the actions of the opponents. Once none of the bidders can improve their response given the opponents' actions, there is evidence that one might have arrived in an equilibrium. Academic literature only offers theoretical proofs for a limited number of circumstances for which the best response algorithm converges (Vorobeychik and Wellman 2008, Brun et al. 2013). Also in the context of the PPP procurement setting, we did not succeed in theoretically guaranteeing the convergence of the heuristic, while the computational results indicate convergence for the majority of the investigated cases.

Due to the complex structure of the pay-off function and the infinite set of possible actions, the identification of the best response is challenging and time consuming. Therefore, the heuristic uses a combination of an electromagnetism-like algorithm and a local search procedure. It is important to note that there is no guarantee that a

[3] In order to avoid notational difficulties, we opted to simplify the notation for this methodological section.

pure strategy equilibrium exists in the case of an infinite number of actions. The algorithm looks into unique equilibria, but of course multiple equilibria might exist and the convergence towards a particular equilibrium is path-dependent. Therefore, the algorithm is executed for a predefined number of starting points. This repetitive structure accounts for the possibility of arriving in alternative equilibria. The pseudo-code for the algorithms can be found in Appendix B.

#### *6.3.4.1 Best response determination*

Optimizing the pay-off function like in Figure 6.2 for a given set of actions for the opponents (indicated as $a_{-p}$) is a computationally intensive task because of the structure of the non-linear pay-off response function. There are two decision variables for each player $p$ that, together, represent the action $a_p$: the investment percentage $i_p$ and the mark-up percentage $m_p$. The best response optimizes:

$$\text{argmax}_{a_p}\, \pi_p^z\big(a_p \big| \theta^z, a_{-p}\big) = \rho_p^z\big(a_p \big| \theta^z, a_{-p}\big) + \delta \mathcal{V}_p^{z+1}(a_p | \theta^z, a_{-p}) \quad (6.10)$$

In order to efficiently determine the global optimum, this paper uses an electromagnetism-like mechanism for global optimization as has been proposed by Birbil and Fang (2003) and whose notation and procedure is utilized here. The attraction-repulsion mechanism of the heuristic succeeds in efficiently browsing through the entire search space and overcomes the danger of arriving in a local minimum, which could be the case when adopting the steepest ascent heuristic. The derivation of the best response is a two-step process. Given the action profile of the opponents $a_{-p}$, a set $\mathcal{T}$ of $T$ solutions is initialized. A solution $t \in \mathcal{T}$ is represented as $x^t = (x_1^t, x_2^t)$, with $x_1^t \in [l_1, u_1]$ the coordinate that refers to the investment level and $x_2^t \in [l_2, u_2]$ the coordinate that refers to the mark-up level. $l_1$ and $l_2$ represent the lower bounds and $u_1$ and $u_2$ the upper bounds. For each initial point, the expected pay-off for player $p$, for whom the best response is derived, equals $f_p(x^t) = \pi_p\big(x^t \big| \theta^z, a_{-p}\big)$. The best solution is stored as $f_p\big(x^{\text{best}}\big)$.

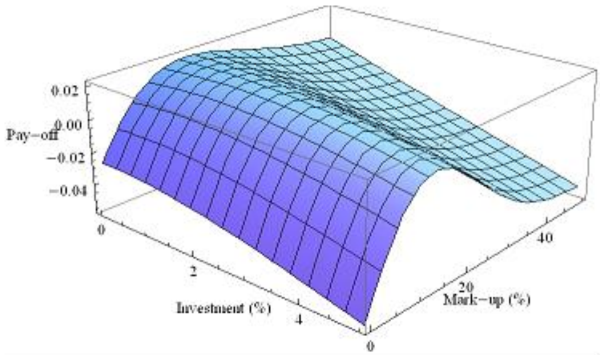


Figure 6.2 Example of the response function $\pi_1^1\left(a_1 \middle| \theta^1 = (1,1,2,0), a_{-1} = (1\%, 20\%, 1\%, 20\%)\right)$

*Electromagnetism step*

A charge for each point $i$ is calculated and represents point $i$'s power of attraction or repulsion:

$$q^t = \exp\left(-2 * \frac{\left(f_p(x^{\text{best}}) - f_p(x^t)\right)}{\sum_{k=1}^{T}\left(f_p(x^{\text{best}}) - f_p(x^k)\right)}\right) \tag{6.11}$$

In the next step, the total forces on each point are computed based on the superposition principle of electromagnetism theory. For the pairwise force calculations, the point that has a higher expected pay-off attracts the other point, while the point with a worse pay-off repels the other point. The forces and moves are calculated for all but the currently best found point, in order to keep the information of the current best point. Furthermore, let $F_n^{tu}$ represent the force exerted by point $u$ on point $t$ for coordinate $n$, with $n = 1$ for the investment direction and $n = 2$ for the mark-up direction. Finally, $F_n^t$ refers to the total force exerted by the other points for coordinate $n$. As a result, one obtains $F^t = \{F_1^t, F_2^t\} = \{\sum_{u \in \mathcal{T} \setminus \{t\}} F_1^{tu}, \sum_{u \in \mathcal{T} \setminus \{t\}} F_2^{tu}\}$ and the force is represented as:

$$F^t = \sum_{u \in \mathcal{T} \setminus \{t\}} \frac{(-1)^{w^{tu}}(x^u - x^t) q^t q^u}{\|x^u - x^t\|^2} \tag{6.12}$$

with $w^{tu} = 0$ if $f_p(x^t) < f_p(x^u)$ and $w^{tu} = 1$ if $f_p(x^t) \geq f_p(x^u)$. In order to move the points, the force vector $F^t$ is normalized into $\bar{\bar{F}}^t = F^t / \|F^t\|$ and a random step length $\eta$ is selected from $U(0,1)$ so that there is a non-zero probability to move to the unvisited regions along the direction of $F^t$. The normalization of the force vector ensures that the new solution is located in the feasible region. In conclusion, all but the previously found best point are moved so that for each $t \in \mathcal{T}\backslash\{\text{best}\}$ and $n \in \{1,2\}$, the respective coordinate becomes:

$$x_n'^t = \begin{cases} x_n^t + \eta \bar{\bar{F}}_n^t (u_n - x_n^t) & \text{if } \bar{\bar{F}}_n^t > 0 \\ x_n^t - \eta \bar{\bar{F}}_n^t (x_n^t - l_n) & \text{if } \bar{\bar{F}}_n^t \leq 0 \end{cases} \tag{6.13}$$

The procedure is iterated a predefined number of times with the newly found coordinates and subsequently, the local search algorithm is executed.

*Example*

Consider a two-player situation for which we want to determine the best response for $p = 1$ and given the action (1,20) for player 2 which refers to a 1% investment percentage and a 20% mark-up percentage. Table 6.1 reports the algorithm values for $T = 4$. The pay-off of player 1 for each point $t$ is given by $f_1(x^t)$, so that the best pay-off is obtained in point 1. The sum of all the differences between the points' pay-off values and the best pay-off is 0.035589 and the charge for point $t = 2$ is found as $\exp\left(-2 * \frac{0.046640-0.040448}{0.035589}\right)$. The distance between point 2 and 3 is 4.4778 and the force that point 3 exerts on point 2 equals $F_1^{23} = (1.7 - 3.5) * \frac{0.7484*0.7061}{4.4778} = -0.2125$ for the investment coordinate and $F_2^{23} = (16.1 - 20.2) * \frac{0.7484*0.7061}{4.4778} = -0.4839$ for the mark-up coordinate. The forces on point 2's investment coordinate from the points 1 and 4 are -0.1022 and 0.0419 respectively, so that the total force $F_1^2 = -0.2728$. After normalizing and generating $\eta$=0.4 as the random variable and defining $(l_1, l_2) = (0{,}0)$ and $(u_1, u_2) = (5{,}30)$, the new investment coordinate for $t = 2$ equals $3.5 + 0.4 * (-0.5725) * 3.5 = 2.6985$.

The electromagnetism procedure is iterated with the previously best found point $(t = 1)$ and with the three newly found points.

| $t$ | $x_1^t$ | $x_2^t$ | $f_1(x^t)$ | $q^t$ | $F_1^t$ | $F_2^t$ | $\bar{\bar{F}}_1^t$ | $\bar{\bar{F}}_2^t$ | $x_1'^t$ | $x_2'^t$ | $f_1(x'^t)$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.3 | 28.4 | 0.0466 | 1 | - | - | - | - | - | - | - |
| 2 | 3.5 | 20.2 | 0.0404 | 0.7061 | -0.2728 | 0.3906 | -0.5725 | 0.8198 | 2.70 | 23.41 | 0.0466 |
| 3 | 1.7 | 16.1 | 0.0414 | 0.7484 | -0.1551 | 0.4541 | -0.3232 | 0.9463 | 1.48 | 21.36 | 0.0494 |
| 4 | 1.0 | 9.7 | 0.0223 | 0.2560 | 0.0804 | 0.6218 | 0.1283 | 0.9917 | 1.21 | 17.75 | 0.0455 |

Table 6.1 Illustration of the electromagnetism heuristic

*Local search step*

The points that result from the electromagnetism step are the input for a local search procedure around each of these points. In each iteration, the investment and mark-up coordinate are modified by applying a random transformation around the original point using a step length vector $\omega$ and a randomly generated point $\kappa$ from a uniform distribution that determines the amount and direction of the perturbation. If the new point results in a higher pay-off, the coordinates are updated and the local search procedure continues from the newly found point. In the end, the best known solution is updated.

*Example*

Let us start from the initial point $(1.48,21.37)$ while the action for the second player is $(1,20)$. This results in a pay-off of 0.049456. Assume that the step length for the investment is 0.3 and 2 for the mark-up. For each coordinate, a random variable is generated from $U(0,1)$: $\kappa = 0.09$ for the investment coordinate and $\kappa = 0.86$ for the mark-up coordinate. In order to allow for positive and negative perturbations, we subtract 0.5 from the randomly generated number, so the new investment coordinate becomes $1.48 + (0.09 - 0.5) * 0.3 = 1.36$ and for the mark-up shift, the mark-up in the new point equals $21.37 + (0.86 - 0.5) * 2 = 22.09$. The point $(1.36,22.09)$ leads to a pay-off of 0.0501 and consequently, the local search continues from this outperforming point.

#### *6.3.4.2 Equilibrium selection*

For a starting point that is randomly selected from the entire action profile space, the best response heuristic is executed until the convergence criterion is satisfied. Convergence occurs as soon as no significant pay-off improvements have been registered in a pre-defined number of loops and as long as a minimum number of loops $BRMINREP$ has been executed. Moreover, the algorithm stops when the number of loops reaches $BRMAXREP$. The convergence is path-dependent, so the algorithm is repeated for $R$ starting points. Afterwards, the $R$ resulting action profiles are clustered according to a distance criterion resulting in $C$ clusters. Points are sequentially assigned to the cluster for which the distance between the point and the average coordinates of the cluster is minimal and smaller than $MAXDIST$. Alternatively, a new cluster is formed. Within each cluster, the coordinate-by-coordinate average of all points belonging to the cluster are calculated together with the pay-off profile. Clusters with a number of points smaller than $MINSUPPORT$ are removed as these might have resulted from a local optimum.

The second step in the equilibrium selection process compares the averages of the clusters and removes any clusters that are dominated by other clusters (i.e., a cluster that has higher expected pay-offs for all players). Subsequently, the clusters are ranked according to the sum of the average pay-offs of all players and the cluster with the highest total pay-off is moving to the refinement stage. The refinement stage executes the best response heuristic again to confirm whether the particular action profile is an equilibrium. If this is confirmed, the resulting reported equilibrium for the state is stored and is used to compute the equilibria in the stage $z-1$. The determination of the algorithm variables are the result of a preceding tuning study with the purpose to trade off computation times and the level of accuracy and to assess the speed of convergence. The final values are reported in Table B.1 of Appendix B.

### 6.3.5 Experimental setting

The computer experiments have been executed in Microsoft Visual Studio 2010 and Wolfram Mathematica 8.0 performs the pay-off calculations. As the risk profile of PPP projects deserves major interest, we are mainly interested in the effect of the level of uncertainty, which is reflected by the knowledge impact parameters $\gamma_i$ (i.e., the variability due to a lack of investment) and $\gamma_e$ (the variability due to a lack of experience). Three sets of scenarios have been developed. Each scenario is executed for every unique combination of experience levels. Section 6.4.2 and Section 6.4.3 give insights into the general dynamics of the equilibrium and rely on the four scenarios that are determined by the parameter values of Table 6.2. We will refer to these as follows: Sc.1 ($\gamma_i = \gamma_e = 0.1$), Sc. 2 ($\gamma_i = 0.1, \gamma_e = 0.05$), Sc. 3 ($\gamma_i = 0.05, \gamma_e = 0.1$) and Sc. 4 ($\gamma_i = \gamma_e = 0.05$). Secondly, Section 6.4.4 covers a case (Sc. 5) with extreme risks ($\gamma_i = 0.2$, $\gamma_e = 0.1$). Thirdly, the impact of introducing government compensation in Sc. 1 and Sc. 5 is assessed in Section 6.4.5. Finally, Section 6.4.6 highlights some noteworthy robustness aspects from a more extensive sensitivity analysis of the cost impact related parameters in a setting with only two experience intervals ($e_u = 2$).

| Parameter | Explanation | Value(s) |
|---|---|---|
| $\gamma_i$ | Maximum risk impact of a lack of investment | 0.05, 0.1 |
| $\gamma_e$ | Maximum risk impact of a lack of experience | 0.05, 0.1 |
| $\beta_i$ | Maximum cost impact of a lack of investment | 0.05 |
| $\beta_e$ | Maximum cost impact of a lack of experience | 0.05 |
| $\sigma$ | Uncontrollable project risk | 0.05 |
| $\lambda_i$ | Investment learning rate | 0.25 |
| $\lambda_e$ | Experiential learning rate | 0.25 |
| $\mu_i$ | Investment cost decrease rate | 0.25 |
| $\mu_e$ | Experience cost decrease rate | 0.25 |
| $d$ | Government compensation level | 0 |
| $\delta$ | Discount rate | 1/1.05 |
| $e_u$ | Maximum level of experience | 5 |
| $(l_1, u_1)$ | Range of investment percentage | (0%, 5%) |
| $(l_2, u_2)$ | Range of mark-up percentage | (0%, 50%) |

Table 6.2 Parameter values for the computer experiment

## 6.4 Experimental results

### 6.4.1 Algorithm performance

For each state of the game, the algorithm looks for the state-specific action equilibrium. As the algorithm is based on a best response heuristic, it is important to assess the convergence performance. A scale with $e_u = 5$ intervals leads to six experience levels on the scale from 0 to 10, which results in 21 experience vectors (0,0), (0,2), (0,4), (0,6), (0,8), (0,10), (2,2), (2,4), …, (10,10) in a two-player setting. Equivalently, a three-player setting with five intervals results in 56 experience vectors. Convergence occurs when the algorithm stops before the maximum number of replications has been reached. For Sc. 1-4, the convergence criterion is met up to a three-project pipeline ($Z = 3$) in the three-player setting. In the two-player setting, convergence issues appeared solely in a three-project pipeline for subgames (0,8) and (0,10) in which experienced players are randomizing within a small area of the action profile space of Sc. 1 between actions without investment on the one hand and with a small investment (0.5%) and a slightly higher (1%) mark-up on the other hand.

In the convergent cases, given the parameters in Table B.1, the search procedure converges already after less than $BRMINREP$ loops towards a specific search region in the action profile matrix. Changing the players' sequence of best response selection does not modify this tendency. In the first loops of the best response algorithm, the electromagnetism step is mainly attributable for the selection of the best response, while in later iterations the local search procedure will be mainly responsible for the determination of the optimizing step. Admittedly, the electromagnetism meta-heuristic increases the complexity of the algorithm. Nevertheless, we could not analytically prove concavity of the expected pay-off function for all the scenarios and in all the instances. Therefore, the meta-heuristic refrains us from arriving in a local optimum and efficiently searches in the entire search space. In the vast majority of the cases, the algorithm reports a single cluster. Only in the two- and three-project context of Sc. 1 and Sc. 2, two equilibria are apparent for the mature markets (8,8,10) and (8,10,10).

### 6.4.2 Impact of the pipeline on the procurement of the first project

Table 6.3 and Table 6.4 report the statistical results of the scenario-by-scenario analysis for the strategic actions in the tender for the first project in a single-, a two- and a three-project environment with two and three players. Within the stochastic game notation, the table compares the actions of the states for a constant experience vector $e$, but for a variable number of remaining projects in the pipeline. So, if a state is represented as $\theta^z = (e_1, e_2, Z - z)$, this section compares the actions for $\theta^1 = (.,.,0)$ with $\theta^1 = (.,.,1)$ and $\theta^1 = (.,.,2)$. A parametric paired t-test has been used to study the paired observations. In order to guarantee the results' statistical robustness, the output of the non-parametric Wilcoxon signed rank test is also reported. The statistical tests confirm the initial expectation that mark-ups are lowered when extra projects are introduced both in the two-player as well as in the three-player case. The drop in mark-ups is the greatest for the inexperienced players, resulting in more competition within the heterogeneous market. An analysis of the investment dynamics tends to point towards decreasing investment percentages when more projects are in the pipeline. Conditioning on the experience levels for the comparison of a three- versus a single-project case with three players indicates an insignificant average absolute drop of 0.001% for inexperienced players (p-value=0.106), towards a significant average 0.02% drop (p-value=0.004) for players with $e_1 = 2$ and $e_1 = 4$ and a drop of 0.045% for players with maximum experience (p-value=0.0003). Looking at the two-player environment in which the investments are generally higher, the results show a significant decrease of 0.24% and 0.05% for players with experience levels 0 and 2 respectively (p-values 0.001 and 0.025), but do report a significant increase for players from experience level 6 onwards.

| 2 players (df = 167) | | Absolute difference | Paired t-test | Wilcoxon test |
|---|---|---|---|---|
| Investment (%) | 2-1 | -0.0055 | 0.3434 | 0.5416 |
| | 3-1 | -0.0287 | 0.05435 | 0.2041 |
| Mark-up (%) | 2-1 | **-0.7468** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| | 3-1 | **-1.2577** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| Pay-off | 2-1 | **-0.0037** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| | 3-1 | **-0.0062** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| Government cost | 2-1 | **-0.0079** | $<2.2*10^{-16}$ | $2.2*10^{-15}$ |
| | 3-1 | **-0.0133** | $7.5*10^{-14}$ | $1.7*10^{-13}$ |

Table 6.3 Average comparisons and associated p-values of the first stage of a two- or three-stage environment with respect to a single-stage environment (2 players)

| 3 players (df = 671) | | Absolute difference | Paired t-test | Wilcoxon test |
|---|---|---|---|---|
| Investment (%) | 2-1 | **-0.0103** | 0.0002 | $3.9*10^{-8}$ |
| | 3-1 | **-0.0166** | $7.3*10^{-7}$ | $1.5*10^{-10}$ |
| Mark-up (%) | 2-1 | **-0.6159** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| | 3-1 | **-1.1308** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| Pay-off | 2-1 | **-0.0019** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| | 3-1 | **-0.0035** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| Government cost | 2-1 | **-0.0058** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| | 3-1 | **-0.0106** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |

Table 6.4 Average comparisons and associated p-values of the first stage of a two- or three-stage environment with respect to a single-stage environment (3 players)

Eventually, the decreasing mark-ups also lead to lower bidder's expected pay-offs for the first project and a lower project procurement cost for the government. According to the aggregated scenario outcomes, the mark-up and consequently also the pay-off drop is largest for the inexperienced players and in the subgames in which mainly inexperienced players are involved. On average, a decrease of 13.53% in the pay-off has been reported in the two-player case and 19.35% in the three-player case when moving from a single-project to a three-project pipeline. Additionally, inexperienced players are sometimes willing to suffer a loss in the first project in order to win the project and obtain a greater experience level for the next project. In general, the percentage-wise drop in pay-offs has a negative slope in the experience level. The reduced mark-ups have positive repercussions on the government expenditures. The government cost for the first project in a three-project pipeline is 1.12% lower in two-player subgames and 0.92% lower in three-player subgames than in the case without a pipeline. In immature markets, savings of 5.14% and 4.13% might be realized in two- and three-player settings respectively.

Furthermore, an ANOVA study of the investment percentage in function of the model parameters and the state-defining values with first-order interaction effects could not support significance at the 5% level of any of the terms related to the number of projects in the pipeline in the three-player case. In the two-player model, both the interaction term of the experience level $e_1$ and the number of projects in the pipeline as well as the interaction term of the competitor's experience level $e_2$ and the pipeline length are highly significant (p-values equal $4.6*10^{-7}$ and $9.8*10^{-5}$ respectively). The ANOVA models for the mark-ups, on the other hand, reveal the main effect and the interaction effects of the pipeline variable. We refer to Appendix C for the full ANOVA results. The ANOVA tests also underline the interaction with the players' experience vector that defines the state variable.

Table 6.5 and Table 6.6 show the action dynamics in the bidding behavior for the first project for a player with experience level $e_1$ with respect to a variable number of projects in the pipeline. Only the scenarios that involve players with experience level zero up to four are reported, but analogous results are apparent for the remaining scenarios. Moving towards a multi-project environment considerably reduces the mark-ups for the inexperienced players. According to these tables, only players with a competitive advantage over all their competitors (e.g., the subgames $(e_1, e_2, e_3)$=(2,0,0), (4,0,0) or (4,0,2) and $(e_1, e_2)$=(2,0), (4,0) or (4,2)) have a tendency to invest more in a multi-project environment than in a single-project setting, which means that players who were already in a beneficial position opt to strengthen their advantage even more. The cases in which a player has an experience level that is equal to or lower than at least one of his opponents point towards decreasing investment percentages. Also for maximally experienced players, we do not find significance for increasing investment levels, regardless of the experience level of the opponents.

| | | Investment (%) | | | Mark-up (%) | | |
|---|---|---|---|---|---|---|---|
| $e_1$ | $e_2$ | $Z=1$ | $Z=2$ | $Z=3$ | $Z=1$ | $Z=2$ | $Z=3$ |
| 0 | 0 | 0.6219 | 0.6053 | 0.5873 | 19.7437 | 17.0625 | 14.6955 |
| | 2 | 0.5523 | 0.4737 | 0.3935 | 17.5292 | 16.0452 | 14.8581 |
| | 4 | 0.4954 | 0.3915 | 0.2948 | 16.7109 | 15.9558 | 15.3513 |
| 2 | 0 | 0.8171 | 0.8627 | 0.9024 | 19.0780 | 16.9524 | 15.1775 |
| | 2 | 0.7472 | 0.7340 | 0.7257 | 16.2857 | 14.8594 | 13.6578 |
| | 4 | 0.6923 | 0.6526 | 0.6146 | 15.1706 | 14.2538 | 13.4889 |
| 4 | 0 | 0.9612 | 1.0556 | 1.1304 | 19.1873 | 17.5786 | 16.2922 |
| | 2 | 0.8858 | 0.9010 | 0.9153 | 16.0608 | 14.9066 | 13.9701 |
| | 4 | 0.8139 | 0.8065 | 0.7998 | 14.7693 | 14.0016 | 13.4085 |

Table 6.5 Actions for the first project in a pipeline with $Z$ stages for a player with initial experience level $e_1$ and competition given by $e_2$. Only the scenarios that involve players with $e_p \leq 4$ are reported.

| | | Investment (%) | | | Mark-up (%) | | |
|---|---|---|---|---|---|---|---|
| $e_1$ | $(e_2, e_3)$ | $Z=1$ | $Z=2$ | $Z=3$ | $Z=1$ | $Z=2$ | $Z=3$ |
| 0 | (0,0) | 0.0605 | 0.0523 | 0.0475 | 17.8555 | 15.5732 | 13.7851 |
| | (0,2) | 0 | 0 | 0 | 17.8903 | 16.3290 | 15.0730 |
| | (0,4) | 0 | 0 | 0 | 18.0219 | 16.8438 | 15.8245 |
| | (2,2) | 0 | 0 | 0 | 18.8658 | 17.4898 | 16.6131 |
| | (2,4) | 0 | 0 | 0 | 19.6958 | 18.5270 | 17.8428 |
| | (4,4) | 0 | 0 | 0 | 21.5371 | 20.7122 | 19.9445 |
| 2 | (0,0) | 0.5342 | 0.5673 | 0.5951 | 16.1461 | 14.2091 | 12.6989 |
| | (0,2) | 0.3885 | 0.3736 | 0.3800 | 15.0596 | 13.6624 | 12.4312 |
| | (0,4) | 0.2778 | 0.2024 | 0.1555 | 14.7467 | 13.8614 | 13.1032 |
| | (2,2) | 0.1340 | 0.1228 | 0.1122 | 15.1770 | 13.8794 | 12.8762 |
| | (2,4) | 0 | 0 | 0 | 15.4669 | 14.5736 | 13.8471 |
| | (4,4) | 0 | 0 | 0 | 15.8346 | 14.9218 | 14.2969 |
| 4 | (0,0) | 0.7180 | 0.7515 | 0.7656 | 16.1467 | 14.6117 | 13.4599 |
| | (0,2) | 0.6477 | 0.6567 | 0.6862 | 14.6991 | 13.5995 | 12.6903 |
| | (0,4) | 0.6021 | 0.5864 | 0.5757 | 13.9064 | 13.0796 | 12.4178 |
| | (2,2) | 0.5549 | 0.5882 | 0.6018 | 14.2170 | 13.1166 | 12.2588 |
| | (2,4) | 0.3966 | 0.3776 | 0.3788 | 13.7333 | 12.9781 | 12.3046 |
| | (4,4) | 0.1812 | 0.1726 | 0.1668 | 14.0469 | 13.2049 | 12.6015 |

Table 6.6 Actions for the first project in a pipeline with $Z$ stages for a player with initial experience level $e_1$ and competition given by $(e_2, e_3)$. Only the scenarios that involve players with $e_p \leq 4$ are reported.

### 6.4.3 Impact of a pipeline on the average expected bidding behavior

Section 6.4.2 solely looked at the bidding dynamics of the first project of the pipeline. A second approach to analyze the dynamics of the bidding behavior compares the average expected investment and mark-up percentages of the players over the entire pipeline. Given the optimal action profiles $a^{*Z}$, the average investment level over te entire pipeline is calculated by taking the sum of the investment levels of each state $\theta^z = (.,.,Z-z)$ for each $z$ weighted with the probability that this state occurs. Consider the three-project pipeline and initial experience vector $(e_1, e_2) = (0,2)$ of Fig. 1. The expected average investment percentage for player 1 equals $(0.6\% + 0.43(1.3\% + 0.50 * 1.6\% + 0.50 * 1.3\%) + 0.57(0.6\% + 0.43 * 1.3\% + 0.57 * 0.8\%))/3 \approx 0.9\%$. These averages are then compared to the situation in which a single project is tendered three times, which means that only the actions and transition probabilities of the state variables $\theta^z = (.,.,1)$ are considered. The average expected pay-offs and government cost may be obtained in a similar fashion.

| 2 players | | Absolute difference | Paired t-test | Wilcoxon test |
|---|---|---|---|---|
| Investment (%) | All | -0.012196 | 0.0687 | 0.1257 |
| | $e_1 = 0$ | **-0.109036** | 0.0007 | 0.0007 |
| | $e_1 = 2$ | **-0.024765** | 0.0240 | 0.0192 |
| | $e_1 = 4$ | 0.000970 | 0.9118 | 0.4785 |
| | $e_1 = 6$ | 0.017302 | 0.0384 | 0.0618 |
| | $e_1 = 8$ | 0.022350 | 0.0087 | 0.0993 |
| | $e_1 = 10$ | 0.020006 | 0.0154 | 0.1936 |
| Mark-up (%) | All | **-0.580689** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| | $e_1 = 0$ | **-0.886568** | 0.0002 | 0.0004 |
| | $e_1 = 2$ | **-0.887977** | $2.2*10^{-9}$ | $7.5*10^{-9}$ |
| | $e_1 = 4$ | **-0.672399** | $1.0*10^{-11}$ | $7.5*10^{-9}$ |
| | $e_1 = 6$ | **-0.459318** | $1.6*10^{-8}$ | $7.5*10^{-9}$ |
| | $e_1 = 8$ | **-0.341360** | $1.0*10^{-6}$ | $7.5*10^{-9}$ |
| | $e_1 = 10$ | **-0.236514** | 0.0004 | 0.0002 |
| Pay-off | All | **-0.002871** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| | $e_1 = 0$ | **-0.007250** | $2.9*10^{-10}$ | $7.5*10^{-9}$ |
| | $e_1 = 2$ | **-0.004809** | $8.4*10^{-15}$ | $7.5*10^{-9}$ |
| | $e_1 = 4$ | **-0.002772** | $2.5*10^{-11}$ | $1.49*10^{-8}$ |
| | $e_1 = 6$ | **-0.001428** | 0.0013 | 0.0004 |
| | $e_1 = 8$ | **-0.000730** | 0.0728 | 0.0004 |
| | $e_1 = 10$ | **-0.000237** | 0.5872 | 0.0156 |

Table 6.7 Scenario-by-scenario comparison of the average strategic behavior in the case of a three-project pipeline and the case with three times tendering a single project (2 players)

| 3 players | | Absolute difference | Paired t-test | Wilcoxon test |
|---|---|---|---|---|
| Investment (%) | All | **-0.010770** | $2.1*10^{-9}$ | $<2.2*10^{-16}$ |
| | $e_1 = 0$ | **-0.003858** | $8.8*10^{-6}$ | $9.3*10^{-5}$ |
| | $e_1 = 2$ | **-0.015447** | 0.0006 | $9.7*10^{-6}$ |
| | $e_1 = 4$ | **-0.014114** | 0.0010 | 0.0002 |
| | $e_1 = 6$ | **-0.006935** | 0.0583 | 0.0071 |
| | $e_1 = 8$ | 0.000406 | 0.9319 | 0.0847 |
| | $e_1 = 10$ | **-0.024669** | 0.0001 | $6.4*10^{-8}$ |
| Mark-up (%) | All | **-0.552494** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| | $e_1 = 0$ | **-1.138677** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| | $e_1 = 2$ | **-0.772383** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| | $e_1 = 4$ | **-0.535272** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| | $e_1 = 6$ | **-0.410947** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| | $e_1 = 8$ | **-0.310890** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| | $e_1 = 10$ | **-0.146796** | $5.1*10^{-7}$ | $8.2*10^{-13}$ |
| Pay-off | All | **-0.001648** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| | $e_1 = 0$ | **-0.002150** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| | $e_1 = 2$ | **-0.002067** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| | $e_1 = 4$ | **-0.001834** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| | $e_1 = 6$ | **-0.001498** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| | $e_1 = 8$ | **-0.001197** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |
| | $e_1 = 10$ | **-0.001142** | $<2.2*10^{-16}$ | $<2.2*10^{-16}$ |

Table 6.8 Scenario-by-scenario comparison of the average strategic behavior in the case of a three-project pipeline and the case with three times tendering a single project (3 players)

Table 6.7 and Table 6.8 report the statistical analysis of the differences and agree with the previously stated findings. The former mark-up results are confirmed so that, from a procurement perspective, bidding becomes more aggressive in the case of a project pipeline than when projects are tendered without communicating the pipeline. The analysis of the average investment efforts in the experiment shows that the pipeline concept does on average not incur extra investment efforts. Nonetheless, conditioning on the experience level reveals the experience-dependent response. The differences in the dynamics are also attributed to the competitive position of the player with respect to the opponents. In the model, pre-tender investment results in a reduction of the uncertainty, so that sometimes more accurate estimations point towards higher project costs. Consequently, bidders might prefer to be less informed and play with the mark-up, win a project and in its turn use the experience for future projects.

### 6.4.4 High-risk situation

A change of the $\gamma_i$ parameter of Sc. 1 to a value of 0.2 refers to a case with high project-related risk (Sc. 5). The observation of the three-player equilibrium results has led to three findings. Firstly, not all subgames could guarantee convergence. In the subgames (0,0,8) and (0,0,10) with a single project for instance, the inexperienced players are looping over strategy profiles in which they both participate or one stays out. Consequently, one might expect that there is an equilibrium in mixed strategies. As the results of a multi-project pipeline rely on the outcome of the single-project case, this non-convergence effect acts as a bullwhip to earlier states of the stochastic game. Secondly, among all scenarios, there are only two cases for which the equilibrium allows participation for all players for the single-project case: subgame (0,0,0) with a 2.1% investment and a 25% mark-up for all participants and subgame (2,2,2) with a 2.4% investment and a 21% mark-up. In all other subgames, the reported equilibrium always suggests that one player should stay out of this engagement (i.e., 0% investment and 50% mark-up). Thirdly, adding extra projects has the same consequences as described earlier, but players who applied a no-participation action in the single-project case, will still prefer to stay out of the market.

As a result, the model argues that it might be unsustainable to invite three contractors for the bid preparation stage in a high-risk project environment. This is an important finding that could not be identified by means of the strategy game methodology of Chapter 4 and Chapter 5. Therefore, the equilibria of a two-player setting are of very high interest. In this vein, the previous results seem to be robust: everyone participates, mark-ups decrease in the length of the pipeline and players with a competitive advantage over their opponent tend to invest more, but the investment gaps are small. Hence, levelled strategic behavior is expected if uncertainty is highly project-dependent.

### 6.4.5 Government reimbursement

In general, one might say that the introduction of a pipeline leads to fiercer competition from a mark-up perspective. Nevertheless, the inexperienced bidders are still significantly less willing to invest in research, which is especially the case in a three-player setting. Therefore, a government reimbursement might help to level the playing field from an investment perspective. In this way the government gives all bidders an opportunity to enter the market which would prevent oligopolistic behavior or hidden collusion among mature bidders for instance. The government determines a compensation percentage $d$ that reflects the fraction of the investment efforts that is reimbursed to all losing bidders. Table 6.9 summarizes the main characteristics of the average bidding equilibrium results of a three-project pipeline for Sc. 1 and high-risk Sc. 5 in a two-player setting and for Sc.1 in the three-player case. The figures use a similar approach as in Section 6.4.3, so that we look at the average bidding behavior, the average pay-off and the average government expenditure over the entire three-project pipeline.

If two players are prequalified, the investment willingness is relatively symmetric for both players, both in the low-risk as well as in the high-risk case. An introduction of a compensation raises the investment willingness. The average mark-up percentages tend to decrease to the level of 40% compensation in the low-risk case, while they increase from 40% compensation onwards in the high-risk setting. Of course, this reimbursement involves additional expenditures for the government, but these extra costs can be partly offset by the savings that result from the pipeline concept.

In the low-risk case with a three-project pipeline, a compensation between 20% and 40% would lead to optimal results: an investment increase and a government expenditure decrease. Interestingly, the average government expenditure in the high-risk setting is lower than in the low-risk environment. Moreover, both players have a considerable investment willingness, making the introduction of a reimbursement policy obsolete, because it would only increase the government cost and inflate the contractors' profits.

| | $d$ | No part.[a] | All invest[b] | Avg. investment | Avg. mark-up | Avg. pay-off | Gvt. cost pipeline | Gvt. cost no pipeline[c] |
|---|---|---|---|---|---|---|---|---|
| 2 players, Sc. 1 | 0% | 0 | 19[d] | 1.50 | 16.91 | 0.0428 | 1.1658 | 1.1716 |
| | 20% | 0 | 21 | 1.83 | 16.52 | 0.0404 | 1.1650 | 1.1716 |
| | 40% | 0 | 21 | 2.20 | 16.35 | 0.0394 | 1.1677 | 1.1748 |
| | 60% | 0 | 21 | 2.61 | 16.39 | 0.0399 | 1.1741 | 1.1816 |
| | 80% | 0 | 21 | 3.08 | 16.70 | 0.0422 | 1.1852 | 1.1930 |
| 2 players, Sc. 5 | 0% | 0 | 21 | 3.67 | 18.78 | 0.0262 | 1.1617 | 1.1681 |
| | 20% | 0 | 21 | 3.99 | 18.72 | 0.0281 | 1.1705 | 1.1773 |
| | 40% | 0 | 21 | 4.35 | 18.85 | 0.0312 | 1.1824 | 1.1896 |
| | 60% | 0 | 21 | 4.75 | 19.19 | 0.0358 | 1.1980 | 1.2055 |
| | 80% | 0 | 21 | 4.93 | 20.02 | 0.0441 | 1.2176 | 1.2255 |
| 3 players, Sc. 1 | 0% | 0 | 4 | 0.60 | 18.09 | 0.0193 | 1.1317 | 1.1377 |
| | 20% | 0 | 7 | 0.95 | 18.15 | 0.0173 | 1.1312 | 1.1374 |
| | 40% | 3[e] | 20 | 1.32 | 18.26 | 0.0160 | 1.1345 | 1.1405 |
| | 60% | 4[e] | 30 | 1.80 | 18.09 | 0.0152 | 1.1423 | 1.1481 |
| | 80% | 5[e] | 40 | 2.46 | 17.69 | 0.0154 | 1.1584 | 1.1644 |

Table 6.9 Aggregate results of the impact of government reimbursement on the equilibrium outcome of a three-project pipeline

[a] Number of subgames in which at least one player does not participate. The total number of subgames is 21 for the two-player setting and 56 for the three-player setting.

[b] Number of subgames in which all players have investment levels greater than 0%

[c] Average cost of tendering three times a single project consecutively

[d] An inexperienced player does not invest for the first project if he is playing against $e_2$= 8 or 10 and $Z$ = 3

[e] A player with experience level 0 in subgames (0,8,8), (0,8,10) and (0,10,10) does not participate when $d$=40%. Moving to 60% and 80% also adds (0,6,10) and (0,6,8), respectively, to the set of no-participation subgames.

A three-player setting will generally lead to fiercer competition and a lower government cost. Nevertheless, Table 6.9 shows that without compensation, it rarely happens that all players of a particular subgame invest. The use of compensation overcomes this dynamic in the majority of the subgames, resulting in a higher average investment. In the subgames where inexperienced players are competing against two mature contractors though, the inexperienced player moves to an equilibrium action in which he does not participate. On average, a compensation of 40% together with a pipeline of three projects is cheaper than a situation without compensation and without a pipeline. So, in the case governments aim for three competing consortia, a combination of both policies leads to promising results.

Section 6.4.4 highlights the mixed equilibrium behavior of the high-risk three-player case, which prevents us from giving a full analysis of the compensation mechanism. Nevertheless, the experiments show that an 80% reimbursement levies the convergence issue and would ensure that all players of the subgame invest in 46 out of the 56 subgames. For the ten remaining vectors, the 80% reimbursement does not serve as a sufficient incentive to make the inexperienced player who is facing two players with an $e_p$ of at least 2 to invest more. Without a compensation, it is only the case in two out of 56 subgames that all participants invest, while one player does not participate in all the other subgames. Nevertheless, in this high-risk setting, it is very expensive to attribute these compensations. Consequently, this analysis could suggest the policy to prequalify only two contractors in a high-risk setting. However, if the government wants to create a levelled field in the long run with three prequalified bidders despite the additional cost in the short run, a compensation could be effective. Nonetheless, since the investment percentages reflect the willingness of the contractor to invest, it should evidently be the government's priority to reduce the (non-value adding) investment requirements.

### 6.4.6 Additional scenarios

In order to investigate the robustness of the results, a full factorial $2^4$ design has been set up with two levels (i.e., 0.05 and 0.1) for the parameters $\gamma_i$, $\gamma_e$, $\beta_i$ and $\beta_e$. The scenarios have been executed for each subgame (i.e., every possible combination of the experience levels) in a two- and three-player setting with $Z = \{1,2,3\}$. For this robustness study, only two experience intervals are considered, so that $e_u = 2$ and a player's experience level is 0, 5 or 10.

First of all, the results for the states with experience vectors (0,10) and (0,0,10) often did not converge (i.e., in 11 out of 16 scenarios and 5 out of 16 scenarios respectively). In these instances, the algorithm loops between different action profiles. The inexperienced players mix their choice between no investment and a high mark-up and a moderate investment with a low mark-up. The experienced player responds accordingly with a low or a high mark-up. It is especially when the parameters that are related to the experiential advantage ($\gamma_e$ and $\beta_e$) are high that these convergence issues occur. Nevertheless, the dynamics of the previous sections are confirmed by this sensitivity study. Mark-ups are decreasing in the number of projects, regardless of the number of players and their respective experience levels. Concerning the investments, the players who have a competitive advantage in the initial stage of the game increase the investment willingness when the project pipeline grows larger.

The limited number of experience intervals underlines the importance of winning a project early in the pipeline. Therefore, the percentage-wise impact of the pipeline on the mark-ups is greater than when $e_u = 5$. According to the aggregated scenario outcomes, the pay-off drop for the first project of a three-project pipeline is largest for the inexperienced players and in subgames in which inexperienced players are involved. On average, a decrease of 73% in the pay-off has been reported in the two-player case and 109% in the three-player case when moving from a single-project to a three-project pipeline. Consequently, inexperienced players are willing to suffer a loss in the first project in order to win it and obtain a greater experience level for the next project. The pay-off drops for the medium experienced player equal 20% and 33% for the two- and three-player setting respectively and for the player with maximum experience, this amounts to an 8% and a 17% drop. As a result, the combined sensitivity findings also confirm the reduction in the government expenditures. A three-project pipeline reduces the procurement cost of the first project with 1.7% in subgames with two players and with 2.2% in three-player subgames.

## 6.5 Special topic: The continuation value

So far, the model has assumed that the continuation value of the final project of the pipeline equals zero. From a practical perspective, this means that the contractor would only believe in the communicated, finite pipeline and does not have any belief in project opportunities beyond the pipeline. This is not illogical due to the long time frames of the project preparation, the budgetary approval and the execution itself. This was reflected in the analytical model by assuming that $\mathcal{V}_p^{Z+1}(a^Z|\theta^Z) = 0$ in equation (6.1).

But how would the dynamics change if this project pipeline is believed to have an infinite nature? As a contractor, one would like to know how to take this into account in the research and mark-up determination. It might become essential to penetrate the market and establish a comfortable competitive position among the construction consortia. The government, on the other hand, is interested in how this would affect the attractiveness of the market.

When the number of projects in the pipeline $Z$ is gradually increased, one soon bumps against the limits of the Markov perfect equilibrium. From a particular number $Z^*$ of projects onwards, which depends on the state of the game, the best response heuristic does not manage to find an equilibrium in unique strategies anymore. Instead, the procedure loops among a set of actions which would suggest to look into mixed equilibria. These are difficult to analyze in this multi-dimensional setting with heterogeneous players. Since a stochastic game with a pipeline of $Z^* + 1$ utilizes the strategic results of a pipeline with $Z^*$ projects, this looping problem for a particular subgame acts as a bullwhip effect through the longer pipeline.

For instance in a case with $e_u = 5$ and three players for which a pipeline with four projects leads to a looping problem in state $(e_1, e_2, e_3, Z - z)$ =(2,4,6,3), the project-project pipeline will have issues to derive the equilibrium for states (0,4,6,4), (2,2,6,4) and (2,4,4,4). The first subgames for which this occurs is for these in which one or two inexperienced players are playing against one or two mature players (e.g., (0,8) or (0,0,10)). In fact, what is happening is that, initially, (one of) the inexperienced player(s) sets a considerably higher mark-up without investment. But once the pipeline becomes longer, they might consider switching to a strategy in which they do invest with a lower mark-up. In this transition period, the equilibrium becomes unstable and players will randomize their behavior, because they are on the verge to moving to another strategy.

Because these challenges are hard to overcome in the model, we preferred to make an approximation for this long-term perspective of the pipeline. The scenario Sc. 1 has been re-executed for the two- and three player setting with one and two projects in the pipeline. However, two different values for the continuation term $\mathcal{V}_p^{Z+1}(a^Z|\theta^Z)$ are defined. This term has been replaced by an infinite pay-off stream that equals the cumulative pay-off of the three-project pipeline without continuation value beyond the pipeline. A first set of scenarios assumes that this cumulative expected pay-off will be obtained every three periods (the "infinite (3 years)" scenarios). A second set of scenarios assumes that this cumulative expected pay-off is obtained every ten periods (the "infinite (10 years)" scenarios).

An example may clarify this approach. To initialize the procedure as described in Section 6.4, we need to define the new continuation value of the last project in the pipeline for equation (6.1) for each possible subgame. The total cumulative expected pay-off of the three-project pipeline is used. Consider for instance the situation of Figure 6.1. To determine the continuation value for this section, the cumulative pay-offs that are given for state (0,2,2) are considered to be the infinite stream of income for the future. Consequently, for the "infinite (3 years)" scenario, the continuation value for player 1 in subgame (0,2), given an interest rate of 5%, is calculated as:

$$\mathcal{V}_1^{Z+1}(a^Z|\theta^Z) = \frac{0.104}{1.05^3 - 1} = 0.660$$

For the “infinite (10 years)” scenario, this present value is given by:

$$\mathcal{V}_1^{Z+1}(a^Z|\theta^Z) = \frac{0.104}{1.05^{10} - 1} = 0.165$$

In a practical setting, this approach actually means that beyond the communicated pipeline, a steady state of the experience levels in the market occurs. In fact, the contractor believes that the market shares are fixed and none of the players is able to obtain more experience. Instead, a continuous stream of pay-offs is expected in the far future. The “infinite (3 years)” scenario generates this research stream every three periods, while the “infinite (10 years)” scenario generates a stream every ten periods.

Figure 6.3 and Figure 6.4 plot the average investment and mark-up decisions according to the experience level of the player. Each line represents a scenario: the finite scenario refers to the original setting without a continuation value beyond the pipeline, the “infinite (3 years)” refers to the fact that the experience levels are fixed beyond the pipeline and a revue stream is expected in cycles of three periods and the “infinite (10 years)” has a ten-year cycle. Each of these three settings is then executed in a single-project setting and a two-project pipeline. One may consider this pipeline as the short-term pipeline in which experience levels can still change, while the continuation value reflects the long-term pipeline with constant experience levels.

The findings are experience-dependent. Nevertheless, the modification of the revue stream has a significant impact on the bidding behavior. Contractors tend to set lower mark-ups, and especially in the “infinite (3 years)” scenario, the mark-ups nosedive for less experienced players. The slope of the curve becomes even increasing in the experience level. There is one exception for this statement: the inexperienced player in the two-player setting. In that case, the behavior is dependent on the experience level of the opponent. In the (0,0)-subgame, inexperienced players tend to move to zero-mark-ups and prefer to make a loss, in order to guarantee a future stream of revenues. However, in the (0,8)- or (0,10)-subgames, convergence issues arise with looping behavior among a maximum mark-up and a zero mark-up, which biases the graph in these subgames.

The change in investment willingness is more subtle, with only minor moves in the three-player setting, except for experienced players who tend to invest less when the future stream of pay-offs grows larger. Also for the investment efforts, the interaction with the opponent contributes in determining the direction of the change. Eventually, it is clear that in the case the pipeline consists of two projects, there are no significant modifications in the aforementioned dynamics.

Last but not least, it is interesting to see how these scenarios impact an immature market, i.e., an initial experience vector or subgame (0,0) or (0,0,0). For the two-player case without a short-term pipeline and without a continuation value, the average investment willingness amounts up to 1.0% with a mark-up equal to 24.7%. Adding the long-term prospects with ten-period cycles diminishes the investment willingness to 0.8% and the mark-up to 8.8%. Increasing the continuation value even more, by considering three-period cycles, results in 2.9% investment efforts and zero-mark-ups. A similar tendency characterizes the three-player setting for subgame (0,0,0). In the original situation, a zero-investment versus 22.8% mark-up is played. In the 10-period cycle, the investment stays 0%, but mark-ups drop to 11.0%. In the more extreme 3-period cycle, the investment slightly increases to 0.62% and now the mark-up becomes 0%.

As a wrap-up of this section, we claim that the continuation value and the expectation about the long-term pipeline might significantly and even dramatically influence bidding behavior. Especially less experienced consortia bid aggressively, willing to suffer losses. Of course, this may be partly explained by an important assumption in the sequential model: winning a contract results in an experience increase, regardless of the *ex post* evaluation of the project. This section draws an extreme picture: experience levels are assumed to stay fixed after the short-term pipeline is finished. In reality, one might expect new entrants and future growth opportunities. Since the truth will be somewhat in the middle, we expect that a continuous flow of pipelines definitely caps the mark-ups, but one might maybe also fear the reduced investments so that the infinite pipeline acts as a trigger for trial-and-error behavior of consortia.

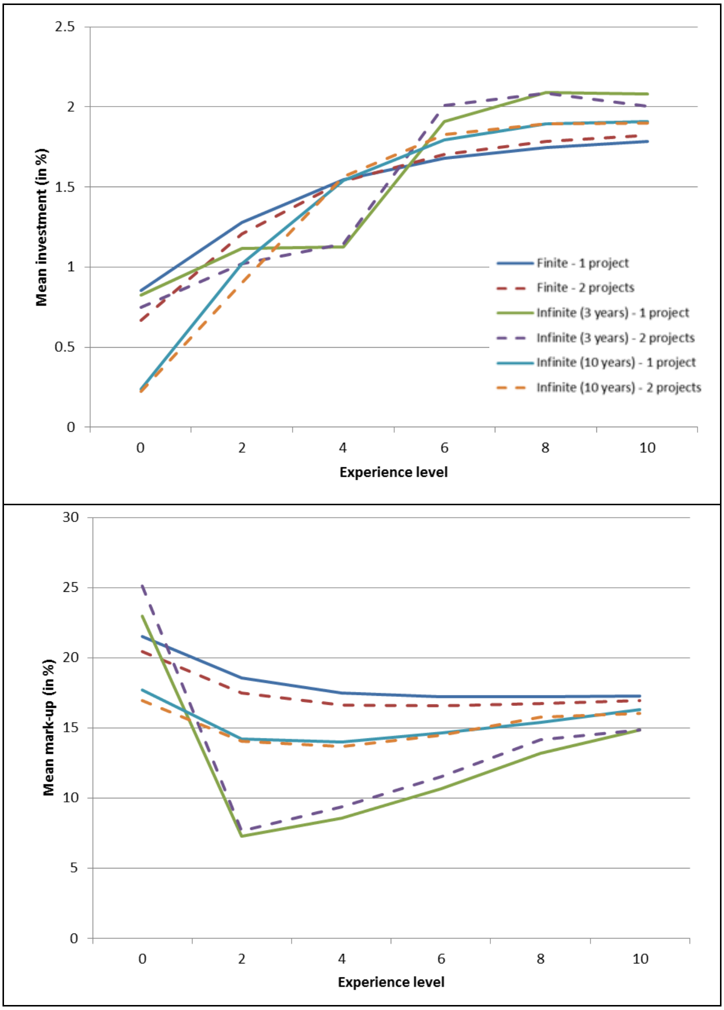


Figure 6.3 Impact of the continuation value on the action equilibrium (2 players)

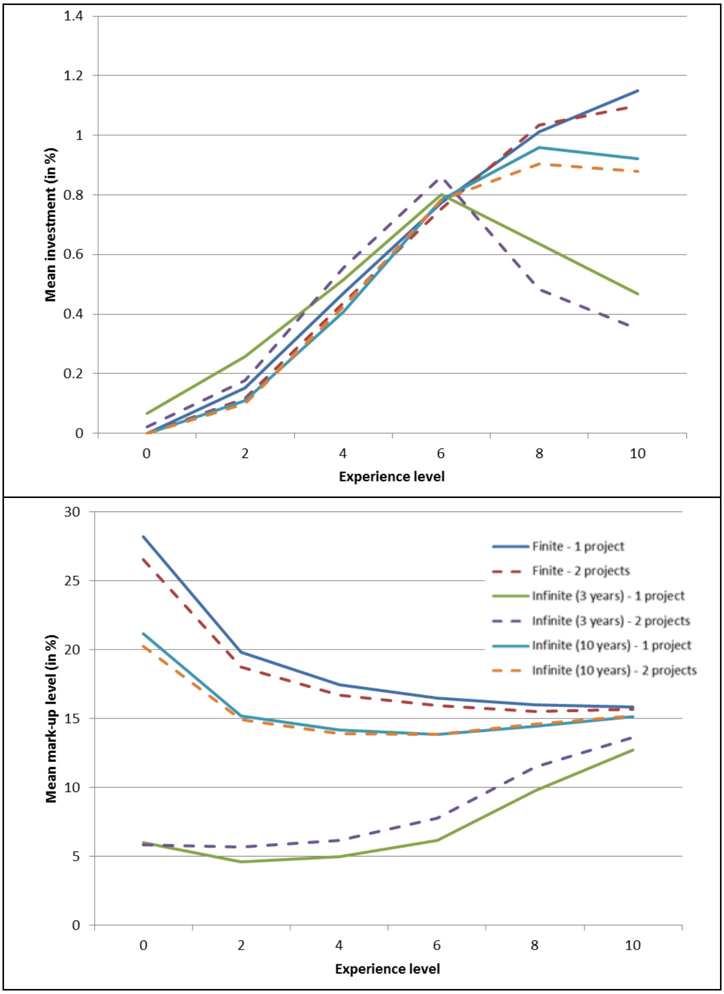


Figure 6.4 Impact of the continuation value on the action equilibrium (3 players)

## 6.6 Conclusion

This chapter offers a second model to study the impact of a pipeline on the dynamic bidding behavior in a PPP setting. The dynamic procurement format has been translated into a sequential procurement auction model in which contractors that are heterogeneous in their cost probability distributions will determine their sequential strategy over the course of a commonly known pipeline and a constant set of bidders. The bidders may change their bidding behavior depending on the state of the stochastic game. Being granted a project results in a knowledge and cost advantage for future projects. This chapter introduces a heuristic best response approach to derive the Markov perfect equilibrium.

Under the assumptions that outline the scope of the chapter, the results support the hypothesis that mark-ups tend to decrease when more projects are included in the pipeline, regardless of the number of bidders. In this vein, the mark-up result is in line with the contemporary sequential auction theory literature. Consequently, bidders are willing to accept lower profits if this might lead to future benefits. Moreover, a continuation value of the final project that is greater than zero (as in Section 6.5) actually amplifies this finding. As a consequence, the government procurement cost tends to have a decreasing nature in the number of projects.

Looking at the upfront investment willingness, there has been only limited support for an increasing trend for players who dispose of a competitive advantage at the start of the pipeline. In all other cases, the investment percentages tend to decrease. Therefore, an investment reimbursement might still be necessary to trigger the consortia's enthusiasm to perform more upfront research. This levels the competition and reduces the risk of a contractor's default, which would always come at the government's expense due to the societal value of PPP projects. The extra cost of investment reimbursements might be partly offset by the reduced mark-ups that result from the pipeline. Nevertheless, in cases with considerable project-specific risks, it might be better to only prequalify two contractors to engage in the expensive tendering process according to the experimental results.

For the private sector, a government's project agenda may definitely have benefits in the sense that it allows to spread out budgets and mitigate risks over several projects. Nevertheless, it leads to fiercer competition and profits could shrink compared to one-shot games. However, it might not be recommended to penetrate a market with an established pipeline and mature players. Entering an immature market could be beneficial and putting a lot of effort together with limited mark-ups in this first project would contribute to the experience base for future projects. Experienced players on the contrary, should increase the investment efforts when a pipeline is introduced if they want to cement their competitive advantage.

The results of this chapter greatly support what has been found in the *ex ante* framework of the previous study. Nevertheless, the methodological approach of this chapter's sequential setting renders additional insights since we have been looking at the full equilibrium profile, while the methodology in the previous chapter considered an approximate equilibrium bidding strategy for a single player. This revealed the fact that high-risk settings with three bidders are unsustainable without the introduction of extra investment incentives (i.e., the government reimbursements). However, how contractors randomize between strategies if no equilibrium in unique strategies was found, remains an open question.

# Chapter 7 Two empirical approaches

The models that have been presented in this dissertation are the result of an investigation of the available literature and the contribution of practitioners. Nevertheless, the results are still subject to assumptions or to biases that cannot be incorporated in computer experiments. For instance, game theory assumes that bidders behave rationally in all instances. Behavioral factors have not been discussed so far. Nevertheless, in order to open the discussion of underlying factors in the decision making, we would like to present the results of two approaches towards this question. Section 7.1 discusses the results of a laboratory experiment. Our models have been transferred into a computer platform that allows real participants to compete against each other using the Z-Tree experimentation software (Fischbacher 2007). For Section 7.2, we have consulted our research network and contacted companies and institutions that were willing to participate in our semi-structured interviews concerning the set-up of the models and the discussion of the results.

## 7.1 Laboratory experiment

In order to grasp some of the behavioral aspects influencing bidding under uncertainty, one may develop a laboratory setting in which subjects compete against each other for fictitious projects. This chapter reveals that the preferred bidding strategies indeed differ from the equilibrium predictions of the previous chapters. The aim is to investigate to what extent the bidding behavior is in line with or overrules the theoretical prediction. Moreover, it is of major concern to confirm or nuance the previously stated dynamics that result from the introduction of governmental policies like the bid cost reimbursement and the project pipeline.

The managerial insights in this chapter are threefold. Firstly, the laboratory experiment supports previous studies its identification of underbidding and hence amplifies the disheartening winner's curse. Secondly, given the inclusion of the costly bid preparation, this chapter pioneers in showing that human interaction and the drive to win could lead to socially suboptimal equilibria. Last but not least, the study of the subject's bidding behavior underlines that the government should carefully design the contracting procedure and its incentive creation mechanisms, especially taking into account contractors' heterogeneity.

Since this chapter paves the road for the introduction of the jargon of laboratory auction experiments, this section starts with a concise overview of the available literature and introduces some important concepts. In Section 7.1.2, the experimental set-up is explained in detail. The research questions and statistical results are described in Section 7.1.3 and Section 7.1.4 respectively. Afterwards, a concluding section relates the results with our theoretical findings.

### 7.1.1 Introduction and lessons from the literature

Laboratory experiments are a common means to analyze auction formats. Mostly, they are set up to compare the theoretical equilibria with the subjects' strategies or to get insights into the equilibrium when the auction models are too complicated to arrive at closed-form analytical expressions. Kagel and Levin (2012) discuss the academic literature on experiments and the different decisions that need to be made. Finally, researchers rely on experiments to study human aspects of decision making like collusion and bid shading (Sherstyuck 2008).

The remainder of this introduction digs deeper into the important decision dimensions of the PPP laboratory experiment and highlights the main concepts of the experimental auction literature.

#### *7.1.1.1 Design of laboratory experiments*

The organization of an experiment requires a large number of participants in order to be able to make statistically relevant conclusions. In a *session*, a group of players takes part in the experiment on a particular date and place. A group plays multiple (independent) games consecutively, which we call *periods*. The number of observations is the number of times a game is played. A game is played multiple times within a group, but also in other groups and in other sessions. Nevertheless, a robust statistical analysis can only be performed on *independent observations*. An observation in a particular group must not be influenced by the interaction with another group. The literature refers to a group as a *cohort*. Within the cohort, there is interaction, because the players from a particular cohort are for instance randomly matched together in each period. However, subjects from a cohort cannot be matched with subjects from another cohort. A session consists of multiple periods that are executed within a cohort, but these multi-period observations are also correlated with each other, which could lead to the problem of pseudo-replication. Consequently, the number of truly independent observations is equal to the number of cohorts. The number of players within a cohort depends on the treatment and the auction format one wants to model. A treatment is defined by a particular set of parameters in the bidding format. The experimenter needs to trade-off the fact that the influence of a single individual decreases when the size of the cohort increases against the fact that the number of independent observations decreases when the size of the cohort increases for a fixed number of participants.

This issue also relates to the number of players that are participating. The following equation expresses the relation among the different decision variables:

$$\text{\# participants} = \frac{(\text{\# treatments })\text{x}(\text{\# independent observations})\text{x}(\text{\#number of players in cohort})}{(\text{\# treatments per player})} \tag{7.1}$$

Within the literature, the number of participants is very diverse with evidence of experiments with 72 participants (Chen-Ritzo et al. 2005) and 212 participants (Georganas and Kagel 2011). Also the length of the experiment is an important characteristic of the design. While experiments with hundred periods exist (Neugebauer and Pezanis-Christou 2007), we find Chen-Ritzo et al. (2005) with only nine periods at the lower end of the spectrum due to the complexity of their multi-attribute procurement setting.

#### *7.1.1.2 Experimental procedure*

The procedure is related to the complexity of the game and the available time. The number of periods is a decision variable that impacts the possibility of learning for a player during the game. This effect also depends on the grouping of participants and the information reporting after each period.

On the one hand, players may be consistently matched to the same opponents. If a player knows that he is always playing in the same group, he might modify his bidding behavior, maybe even rendering collusive behavior. Nevertheless, Leufkens et al. (2007) claim in their sequential auction experiment that cooperation is not occurring in a four-player setting. The other option is to randomly regroup participants in each period (Cason et al. 2011) or, as is the case in our setting, based on a preset profile matching protocol (Haruvy and Katok 2007).

Symmetry in information is a common assumption in analytical auction models, while this is often violated in practice. In this vein, the attribution of types is also a decision that requires some thought. Güth et al. (2005), for instance, study the difference between weak and strong players in asymmetric auctions. The player's type may be randomly generated at the beginning of a period (e.g., Cason et al. 2011, Watanabe and Nakabayshi 2011), players may switch roles after a number of periods (Jog and Kosmopoulou 2014) or there is no change in the asymmetric types (e.g., Lunander and Nilsson 2004, Güth et al. 2005, Brunner et al. 2010). Also the amount of information that is given after each period can be symmetric or asymmetric and requires careful consideration as the explicitation of reference points could have a great impact on the decision-making.

A next step concerns the organization of the treatments. In a *within-subject* design, participants play several treatments and the change in behavior can be easily observed by the experimenter (Brosig and Reiβ 2007, Cason et al. 2011). The advantage is that fewer participants need to be recruited which trades off against the fact that transition effects or order effects may be apparent. Cason et al. (2011) solve this threat by randomizing the sequence of conditions. At the opposite end, Chen-Ritzo et al. (2005) opt for a single treatment per session, which is called a *between-subject* design.

#### *7.1.1.3 Dealing with uncertainty*

From a traditional auction perspective, the buyer faces a certain amount of uncertainty in the value of the object to procure. The literature is traditionally divided in two categories: private value auctions and common value auctions.

In auctions with a private value component, the player has a personal valuation of the object that he knows with certainty, but the uncertainty lies in the valuation of the other players. Typically, the valuations are independently generated from a distribution. In the symmetric case, these probability distributions are the same for all participants (e.g., Neugebauer and Pezanis-Christou 2007, Goeree et al. 2013). In the asymmetric case, the values are generated from distributions that are different for the players. Typically, the distributions are known by all players (e.g., Lunander and Nilsson 2004, Jog and Kosmopoulou 2014). Finally, some experimental setups are combinations of the symmetric and asymmetric case. The sequential auction in Leufkens et al. (2007) accounts for synergies so that the distributions for the second auction are asymmetric. Grimm et al. (2006) start with a symmetric situation, but allow players to invest, resulting in a more beneficial probability distribution.

In auctions with a common value component, the value for all bidders is equal, but uncertain. The value of a project or object is selected from a (known) distribution, but the players receive a signal about the value. Early example studies include Capen et al. (1971) and Kagel and Levin (1986).

However, Pinkske and Tan (2005) underline the fundamental concern whether practice allows for these two distinct classes. Laffont et al. (1995) discuss that most real-life applications, like the one in this dissertation, have a combination of a common and a private value component.

#### *7.1.1.4 Practicalities*

From a practical angle, the experimenter makes a decision on the organization of a session. The available time is limited. The time per period could be bounded in order to reduce the total time of the experiment. Sessions typically take 90 to 180 minutes. In this respect, the majority of studies offer a monetary compensation to the participants when they participate on a voluntary basis. Experimental currency units are converted into a real currency (Leufkens et al. 2007, Cason et al. 2011, Jog and Kosmopoulou 2014). In asymmetric auctions, the profits of advantaged participants could be higher, which would lead to a feeling of injustice (Goeree et al. 2013) that could be compensated by differences in the exchange rate depending on the role of the participant (Georganas and Kagel 2011). Last but not least, the explanation of the experiment needs to be complete and clear. A combination of an oral briefing and written guidelines is key. Finally, some trial periods are usually introduced to make sure everyone understands the setup, although these have the disadvantage that some information on the first real period is lost due to learning effects of the trial periods.

### 7.1.2 Experimental design

#### *7.1.2.1 Aims of the experiment*

The purpose is to design a bidding model that imitates tendering for complex PPP projects. In line with the previous chapters of this dissertation, each bidder makes an investment decision that results in a lower expected project cost and improves its accuracy. Besides, each bidder makes a mark-up decision that reflects the risk premium and the profit margin.

It is impossible to test each scenario that has been discussed in this dissertation, so the number of treatments is limited and is outlined in Section 7.1.2.3. First, the experiment examines the impact of the bidding environment (or the experience vector) on the selected strategy. A player can have previous experience or not, denoted by E and I respectively. An experienced contractor has an advantageous cost probability density with respect to an inexperienced player. A lower expected project cost and a smaller standard deviation reflect the advantage. The experiment looks at the impact of a two- and a three-player environment with experienced and inexperienced players.

Apart from the bidding environment, we want to investigate the impact of the risk structure that is reflected in the variance of the cost probability density. Last but not least, we look at the impact of governmental policies, like attributing a reimbursement for investment efforts in case of a loss and the impact of adding a second project to the sequence.

#### *7.1.2.2 Participants*

The experiments took place at the Faculty of Economics and Business of KU Leuven. Students were recruited from the courses *Integrated Quality Management* (*Integrale Kwaliteitsbeheersing*) and *Project and Production Scheduling*. Since these courses are part of the Master in Business Engineering program, we could assume that, after a brief recap, students are familiar with the necessary understanding concerning probability theory. The experiment was part of the compulsory assignments of the respective courses. In total, six sessions have been organized with each 30 participants. 202 students registered for a session depending on their availability. In order to account for no shows, some of the subjects were randomly selected to be part of the reserve list. Each session had the same setup, but the treatments that have been tested in each session were different.

The main limitation of this setup is that we have only invited students to participate in this experiment, while a more trustworthy setup would entail project managers. This point is also discussed in the literature with for instance Dyer et al. (1989[a]) and Falk and Heckman (2009) being in favor of the use of students and Engelbrecht-Wiggans et al. (2007) claiming that people that are familiar with the bidding setting considerably better approach the equilibrium while inexperienced participants (e.g., students) consistently underbid. Nevertheless, since we aim to test different scenarios (or treatments), a large number of participants is required in order to have sufficient independent observations. Therefore, we preferred to perform this study with business students.

#### *7.1.2.3 Treatments and cohorts*

In order to obtain a satisfactory number of independent observations, we need to limit the number of treatments to test. In three out of six sessions, participants were competing against only one opponent. These are the two-player treatments. In the remaining sessions, each participant was playing against two competitors, i.e., the three-player treatments. Within these two classes of sessions, three situations have been tested:

1) A base case setting with a single project being tendered in each period;
2) A single-project setting in which the losing bidders are reimbursed with 50% of their research investment efforts;
3) A setting in which each project consists of two projects: in the case an inexperienced player wins the first project, he or she becomes experienced in the second tender.

Within each session, two conditions are sequentially tested: a low-risk setting and a high-risk setting. Consequently, this leads to twelve treatments for this bidding experiment. Table 7.1 lists the treatments and their representation.

| | | Low risk | High risk |
|---|---|---|---|
| 2 players | 1 project, no compensation | 2/1/L | 2/1/H |
| | 1 project, 50% compensation | 2/C/L | 2/C/H |
| | 2 projects, no compensation | 2/2/L | 2/2/H |
| 3 players | 1 project, no compensation | 3/1/L | 3/1/H |
| | 1 project, 50% compensation | 3/C/L | 3/C/H |
| | 2 projects, no compensation | 3/2/L | 3/2/H |

Table 7.1 Overview of treatments and their codification "number of players/setting/risk"

In order to investigate the possible diversification of strategies with respect to the differences in experience levels, we have randomly attributed a role to the participants: 50% of the players are experienced and 50% of the players are inexperienced. Being experienced means that this participant has, on average, an advantage in the expected cost (i.e., a smaller mean value of the cost probability density) and a knowledge advantage (i.e., a smaller variance of the cost probability density). The role of the players did not change during the session.

The participants are divided in groups or cohorts, consisting of six players. The participants of the experiment are unaware which players are part of their group. Each group consists of three experienced and three inexperienced players. For each period of the game, the participants from the same cohort are randomly matched. This is necessary to avoid collusive behavior. A subgame is defined as a combination of experience levels. Since we only include two experience levels (i.e., E for the experienced player and I for the inexperienced player), there are three subgames in the two-player case (i.e., I/I, I/E and E/E) and four subgames in the three-player setting (i.e., I/I/I, I/I/E, I/E/E and E/E/E). Consequently, with three experienced and three inexperienced players in a cohort, the following number of combinations for matching are obtained:

- In the two-player case:
    - 3 permutations for I/I matching
    - 9 permutations for I/E matching
    - 3 permutations for I/I matching

- In the three-player case:
  - 1 permutation for I/I/I matching
  - 9 permutations for I/I/E matching
  - 9 permutations for I/E/E matching
  - 1 permutation for E/E/E matching

One might argue that the single permutation (for I/I/I and E/E/E) might lead to collusive behavior. Nevertheless, this is usually not the case in single-shot games with three players and without the possibility of communication.

Given this random matching within a cohort, we only acquire one independent observation per cohort within this auction setting. This limits the possibilities of finding statistical significance for the research hypotheses. Therefore, we have five cohorts for each session. Given that six sessions have been organized and that there are six participants in each cohort, the entire experiment required the participation of 180 students.

#### *7.1.2.4 Process of a period*

At the start of the experiment, the participants are attributed a specific role: experienced or inexperienced. In each period, the software randomly selects an actual base cost that is the same for all bidders but that is not revealed to the bidders. Subsequently, the participant needs to enter an investment percentage and a mark-up percentage for each possible combination of experience levels of the opponent(s). The investment choice determines the remaining variability of the cost probability distribution. Moreover, the investment decision will have an impact on the actual cost of the project. In line with assumptions 3 and 4 from Section 3.2, investing more results in a lower expected actual cost and a smaller standard deviation of this cost probability density. Of course, investment costs money (i.e., € 10,000 per percentage point while the project cost will be around € 1,000,000). The impact of the decision in the high-risk sessions is shown on the strategy sheet of Figure 7.1. These values can be found by applying the following parameter values to equations (3.5) and (3.6) : $\beta_i = 0.1, \beta_e = 0.05, \gamma_e = 0.1, \lambda_i = \lambda_e = \mu_i = \mu_e = 0.25, \sigma = 0$ and $\gamma_i = 0.1$ for the low-risk treatments and $\gamma_i = 0.2$ for the high-risk treatments. However, the direct cost impact is here calculated as a discount instead of a penalty.


INEXPERIENCED

| Investment % | Average cost | Standard deviation |
|---|---|---|
| **0** | 1.000 | 22.36% |
| **0.25** | 0.994 | 21.28% |
| **0.5** | 0.988 | 20.29% |
| **0.75** | 0.983 | 19.36% |
| **1** | 0.978 | 18.51% |
| **1.25** | 0.973 | 17.72% |
| **1.5** | 0.969 | 17.00% |
| **1.75** | 0.965 | 16.33% |
| **2** | 0.961 | 15.72% |
| **2.25** | 0.957 | 15.16% |
| **2.5** | 0.954 | 14.65% |
| **2.75** | 0.950 | 14.18% |
| **3** | 0.947 | 13.76% |
| **3.25** | 0.944 | 13.37% |
| **3.5** | 0.942 | 13.02% |
| **3.75** | 0.939 | 12.70% |
| **4** | 0.937 | 12.42% |
| **4.25** | 0.935 | 12.16% |
| **4.5** | 0.932 | 11.92% |
| **4.75** | 0.930 | 11.71% |
| **5** | 0.929 | 11.53% |

EXPERIENCED

| Investment % | Average cost | Standard deviation |
|---|---|---|
| **0** | 0.980 | 20.90% |
| **0.25** | 0.974 | 19.74% |
| **0.5** | 0.969 | 18.66% |
| **0.75** | 0.963 | 17.66% |
| **1** | 0.958 | 16.72% |
| **1.25** | 0.953 | 15.84% |
| **1.5** | 0.949 | 15.02% |
| **1.75** | 0.945 | 14.27% |
| **2** | 0.941 | 13.56% |
| **2.25** | 0.937 | 12.91% |
| **2.5** | 0.934 | 12.30% |
| **2.75** | 0.931 | 11.74% |
| **3** | 0.928 | 11.23% |
| **3.25** | 0.925 | 10.75% |
| **3.5** | 0.922 | 10.31% |
| **3.75** | 0.919 | 9.91% |
| **4** | 0.917 | 9.54% |
| **4.25** | 0.915 | 9.20% |
| **4.5** | 0.913 | 8.89% |
| **4.75** | 0.911 | 8.60% |
| **5** | 0.909 | 8.34% |

Figure 7.1 Investment impact in the high-risk treatments

In the next stage of the game, which is executed in the background, the participants within the same cohort, are randomly matched. As stated in the previous paragraph, the participants needed to enter investment and mark-up percentages for each possible combination of experience levels for their opponents. Consequently, in the two-player sessions, two investment and two mark-up percentages are required (i.e., for opponent being I or opponent being E), while three investment and three mark-up levels are requested in three-player settings (i.e., for opponents being I/I, I/E or E/E). Figure 7.2 represents the input screen of session 3/1/L. The reason why participants are randomly matched is to avoid learning effects or biased results due to a focus on particular scenarios. Therefore, we follow the method of Dyer et al. (1989[b]) to only match the participants after the input stage. An example of the matching protocol in a three-player setting is shown in Table 7.2. The computer program then selects the appropriate investment levels and mark-up levels according to the outcome of the matching.

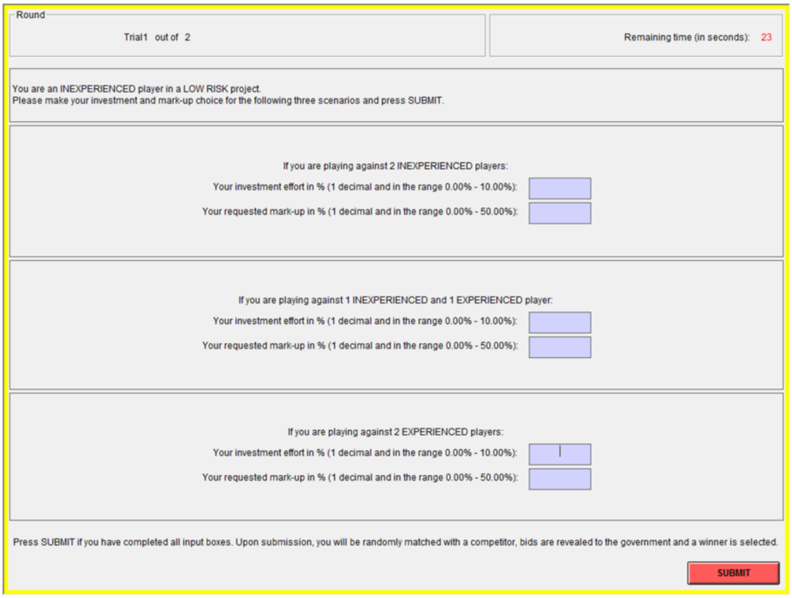


Figure 7.2 Input screen for session 3/1/L

The investment decision then modifies the base cost given the fractions shown on Figure 7.1, arriving at the average cost which will also be the actual cost in the case this bidder wins. The player-dependent actual cost (as the actual cost also depends on the experience and investment) is only revealed to the winning bidder. Moreover, the standard deviation of the cost probability distribution is computed as the investment-dependent percentage of the average cost. Now that the software has shaped the cost probability density, it randomly selects a cost for this player and applies the mark-up that the participant has entered. This is the resulting bid.

| Group | No Experience | | | Experience | | |
|---|---|---|---|---|---|---|
| Period | Q | R | S | X | Y | Z |
| 1 | 1 | 2 | 1 | 1 | 2 | 2 |
| 2 | 1 | 1 | 2 | 1 | 2 | 2 |
| 3 | 1 | 1 | 1 | 2 | 2 | 2 |
| 4 | 1 | 1 | 2 | 2 | 2 | 1 |
| 5 | 2 | 1 | 1 | 2 | 1 | 2 |
| 6 | 1 | 2 | 1 | 2 | 2 | 1 |
| 7 | 1 | 1 | 1 | 2 | 2 | 2 |
| 8 | 2 | 1 | 1 | 1 | 2 | 2 |
| 9 | 1 | 1 | 1 | 2 | 2 | 2 |
| 10 | 2 | 1 | 1 | 2 | 1 | 2 |
| 11 | 1 | 1 | 2 | 2 | 1 | 2 |
| 12 | 1 | 2 | 1 | 2 | 2 | 1 |
| 13 | 1 | 1 | 1 | 2 | 2 | 2 |
| 14 | 1 | 1 | 2 | 2 | 1 | 2 |
| 15 | 1 | 1 | 2 | 1 | 2 | 2 |
| 16 | 2 | 1 | 1 | 2 | 2 | 1 |
| 17 | 1 | 2 | 1 | 1 | 2 | 2 |
| 18 | 1 | 1 | 1 | 2 | 2 | 2 |
| 19 | 1 | 2 | 1 | 2 | 2 | 1 |
| 20 | 2 | 1 | 1 | 2 | 1 | 2 |

| Sub-game | No Experience | | | Experience | | |
|---|---|---|---|---|---|---|
| Period | Q | R | S | X | Y | Z |
| 1 | A | B | A | A | B | B |
| 2 | A | A | B | A | B | B |
| 3 | C | C | C | D | D | D |
| 4 | A | A | B | B | B | A |
| 5 | B | A | A | B | A | B |
| 6 | A | B | A | B | B | A |
| 7 | C | C | C | D | D | D |
| 8 | B | A | A | A | B | B |
| 9 | C | C | C | D | D | D |
| 10 | B | A | A | B | A | B |
| 11 | A | A | B | B | A | B |
| 12 | A | B | A | B | B | A |
| 13 | C | C | C | D | D | D |
| 14 | A | A | B | B | A | B |
| 15 | A | A | B | A | B | B |
| 16 | B | A | A | B | B | A |
| 17 | A | B | A | A | B | B |
| 18 | C | C | C | D | D | D |
| 19 | A | B | A | B | B | A |
| 20 | B | A | A | B | A | B |

Table 7.2 Example of the matching procedure for three-player treatments. The left table shows the division in groups within each cohort and the right table shows the respective subgame in order to select the correct input data.

The winner of the period is the one who has submitted the lowest bid. The losing bidders lose their investment, while the pay-off for the winner is given by the proposed bid minus the actual cost of the project minus the investment in research. The output screen for a participant shows whether the competitor(s) was/were experienced or inexperienced, the participant’s cost estimate and the resulting bid, the lowest submitted bid and the identity of the winner (I or E) followed by the participant's personal stepwise pay-off calculation (Figure 7.3). Consequently, the pay-offs of the opponents are not revealed.

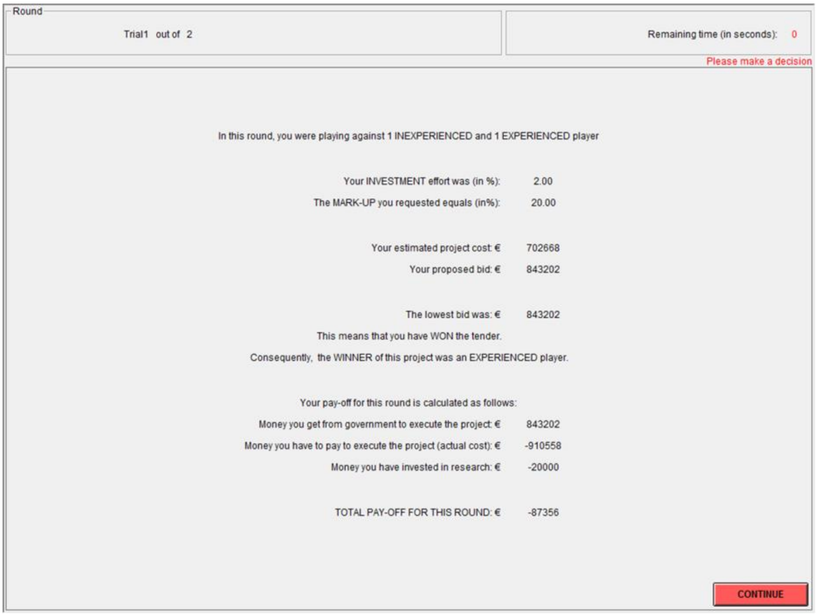


Figure 7.3 Output screen for session 3/1/L

In the single-project treatments, the period ends, pay-offs are reset to zero and the next period commences with a new input screen. In the two-project treatments, there is an additional stage after this output stage. A new input screen appears, but now only a single investment and a single mark-up needs to be entered. This is because the participants will be matched to the same opponent(s) for the second tender. Nonetheless, if an inexperienced player has won the first project, he or she becomes experienced for the second project. Experienced players stay experienced regardless of whether they won or lost the first tender. As a result, at this stage, each participant perfectly knows the identity of the opponents (i.e., the experience levels in the subgame). Once all bidders have entered their investment efforts and mark-ups, the software simulates and subsequently compares the bids. The profits and losses are added to these from the first project to which an interest of 5% has been applied in order to account for the timing aspect of the pipeline. After this second output stage, pay-offs are reset and a new period starts.

#### *7.1.2.5 Example*

Consider the 3/1/L session and a player that is inexperienced. In the input screen, the subject needs to enter the investment and mark-up choices for the three possible subgames:

- In the case of two inexperienced players: 2% investment, 15% mark-up;
- In the case of one inexperienced and one experienced player: 1.5% investment, 18% mark-up;
- In the case of two experienced players: 1% investment, 18% mark-up.

Once all players from the same cohort have filled out the data input boxes, the software performs some computation steps in the background and the player is randomly matched with two other players. These appear to be both inexperienced. Therefore, the software selects the 2%-15% decision combination. Firstly, a cost base is selected that is the same for all players. In this example, the cost base is € 962,314. In the second step, the computer shapes the cost probability distribution based on the investment choice and the experience level. The 2% investment effort results in an average cost factor of 0.961 and a standard deviation of 11.70% in the low-risk scenario. Consequently, the actual cost in case he wins amounts to 0.961*962,314= € 924,784 and the standard deviation is 11.70%*924,784= € 108,200. From this distribution, the program randomly selects a value that equals the cost estimate for the contractor: € 900,145. The program then applies the mark-up to this cost estimate: 900,145*(1+15%) = € 1,035,167 which is the bid that is sent to the government. The software follows the same procedure for the opponents, resulting in a bid of € 1,014,362 for competitor 1 and € 1,245,101 for competitor 2. Consequently, this player has lost the tender and the pay-off equals his lost investment or € -20,000.

Alternatively, imagine that the software selected a cost estimate of € 824,701 with all other figures remaining constant. This would result in a bid of € 948,406. In this case, the player wins the tender and the pay-off obtained in this period equals:

948,406 (proposed bid) – 924,784 (actual cost) – 20,000 (investment effort) = € 3,622.

#### *7.1.2.6 Process of a session*

The participants are randomly assigned to a computer in the room. They have received an envelope with the necessary information about the session. It consists of a protocol, registration sheets and a feedback sheet. Moreover, they are requested to sign an informed consent form[4] that ensures that everyone is willing to participate and knows about the purpose of the research. They also receive an information sheet with data concerning the assumptions and the impact of their actions, which has been further explained in Section 7.1.2.4.

Afterwards, the experimenter gives a thorough explanation of the purpose and the process of the experiment. The instructions last about 30 to 40 minutes. A full version of the protocol of an example session can be found in Appendix D. After the explanation, there is the possibility to ask questions. Afterwards, the experimental software is started. The Z-Tree software is used for the implementation of the experiment (Fischbacher 2007). Each session is divided in two parts: a low-risk part and a high-risk part. The sequence of low-risk and high-risk is randomly determined. Then, at least two guided trial periods for the first part of the session are made to get familiar with the software, the game parameters and the process of the period. Afterwards, the payable periods start. The number of periods played equals 20 for the treatments 2/1, 2/C, 3/1 and 3/C, 16 for 2/2 and 13 for 3/2. The aim was to limit the total duration of the experiment to two hours and as the number of inputs differs for the different sessions, the number of periods has been adjusted accordingly. After the first part of the session, there is a short break before the second part takes off. Also the second treatment of the session starts with at least two trial periods.

[4] For the organization of the experiment, we received approval from the ethical commission of KU Leuven (SMEC, Sociaal-Maatschappelijke Ethische Commissie). The approval number is G-2014 10 061.

At the end of the experiment, the participants are requested to leave their personal details for the profit calculations and to fill out a feedback form on which they had to write down their strategy: “how did you play against (in)experienced players?”, “did you apply a different strategy in the high-risk or low-risk setting?”.

A debriefing session has been organized to inform the participants about the outcome of the experiment and to show the most important differences within and between the sessions.

A final aspect that is worth noting concerns the compensation mechanism and score calculation. Also from this perspective, one needs to avoid that participants are optimizing the entire game. In each period, we study a single-shot setting in the single-project treatments or a two-project setting in treatments 2/2 and 3/2. Therefore, after each period, the pay-offs are reset to zero. To calculate the score of the participants, six periods are randomly selected in each of the sessions. For these periods, the average pay-offs are calculated and compared to the average pay-off within the respective cohort. The pay-offs of the participants are transformed into a standard normal distance from the average. These values represent the score. Since the experiment is part of the assignments in the curriculum, we decided not to reward the participants in monetary terms. Nevertheless, a show-up fee was attributed to the students in the form of a teambuilding activity with the entire group.

### 7.1.3 Research questions

The purpose of this study is to investigate how the theoretical results with respect to the equilibrium bidding strategies and their dynamics differ from a situation with human interaction. When we offer the same bidding model (i.e., cost probability distributions and parameters) to a computer or to a group of people: how do the respective equilibria relate? First of all, Section 7.1.4.3 studies whether there is a gap between the equilibria in the laboratory experiment and the theoretical Nash equilibrium.

A second set of questions relates to the dynamics of the equilibria. The previous chapters have studied the impact of contingencies, the number of shortlisted bidders and a bidder's competitive position on the investment and bidding results. This study hopes to identify whether the findings from the laboratory experiment confirm or nuance the findings from the computer experiments.

Last but not least, the government, as the developer of the tendering process, has an important stake in the resulting strategy equilibrium profile. Therefore, this study assesses how the policies of pre-tender investment reimbursements and a (short) pipeline of projects are perceived by bidders.

### 7.1.4 Results

The analysis of the experimental outcomes is a challenging task and one needs to beware of underlying aspects and hidden features of the experiment that might have an influence on the statistical analysis. Therefore, this section undertakes a robust statistical analysis before discussing the most important learnings in Section 7.1.5. Moreover, the number of independent observations is rather limited. As discussed in Section 7.1.2.3, the experiment only deals with five cohorts per treatment. Since the people within a cohort interact, this only leads to a single independent observation per cohort. Consequently, the experiment delivers five independent observations for each treatment. A parametric analysis on the basis of the limited number of data points would require important assumptions on the data structure that would not be guaranteed. Therefore, the analysis in this section is based on a descriptive analysis, together with non-parametric statistical tests.

Suriya (2013) claims that a minimum of eight independent observations leads to robust statistical results of the non-parametric tests, but some papers, like ours, do consider less independent observations for all or some treatments (e.g., Haruvy and Katok 2007, Georganas and Kagel 2011). However, a lot of information is lost in a non-parametric analysis because these tests are all based on averages within a group over a number of periods, so that a lot of intra-group variability is concealed

(Goeree et al. 2013). Hence, this section also develops a mixed effects model to study the impact of the treatments on the bidding results. Albeit a parametric approach, this study supports the non-parametric findings which is also the case in other parametric regression studies (e.g., Songchoo and Suriya 2012, Kiatkarun and Suriya 2013).

#### *7.1.4.1 The periods of study*

Before studying all the results, it is important to decide which periods will be taken into account. One needs to reckon the fact that in the periods at the beginning of the session, the participants are still learning about the game, the decision variables and the parameters. Moreover, as the total number of periods is shown, also the final round could lead to biased behavior. We observed that the variance in the average responses per group in the single-project treatments is larger when we study periods 5-9 than when periods 15-19 are considered. Selecting only a single period to study the behavior might also bias the results and therefore the data from the final five periods of each treatment (not taking into account the last period) are selected to undergo the statistical analysis.

This results section also compares the realized pay-offs with the pay-offs in the equilibrium of the computer experiment. In order to obtain sufficient data points to make a valid comparison, two measures have been taken. Firstly, in the single-project scenarios, the pay-offs of ten periods have been considered to limit the impact of pay-off outliers. Due to the lower number of executed periods, only five periods are considered in the two-project treatments. Secondly, in line with a similar procedure in Dyer et al. (1989[b]), the pay-offs in each round have been calculated for all players in all possible matching combinations within the cohort, averaged for each scenario.

The generation of random numbers for the estimated cost simulation is an important step in the laboratory experiment and greatly influences the pay-offs (i.e., if a “very negative” random number is chosen as the cost, one will considerably underestimate the cost which could lead to a larger probability of winning, but with a negative pay-off). This outcome could then change the strategic behavior in subsequent periods. As it might be necessary to reduce the bias when comparing the bidding behavior over treatments, the same set of random variables has been applied in the different sessions for the respective periods (Brosig and Reiβ 2007, Brunner et al. 2010). This method hopes to account for any biases in the behavior that are due to randomness.

#### *7.1.4.2 Statistical tests*

A plethora of statistical tests is available to study the bidding outcomes from a non-parametric or parametric angle. Which test to choose depends on the interrelation between the observations and the hypothesis that is tested. Nonetheless, because of the very limited number of independent observations, the non-parametric alternatives are preferred. This paragraph lists the non-parametric tests and the reason why these are selected.

A first set of hypotheses investigates the difference between the observed bidding behavior in the experiments and the prescribed theoretical bidding behavior. In a parametric setting, this study would involve a one-sample t-test. The non-parametric alternative is the *one-sample Wilcoxon signed rank test* that tests whether the median of a data set equals a specified value.

While this first set of hypotheses compares the behavior with a fixed (theoretical) number, the remainder of the tests compares the dynamics of the behavior of the players themselves. The alternative hypotheses are derived from the expected dynamics that the theoretical equilibrium outcomes predict.

A second set of hypotheses compares the behavior of the same players in different conditions. This is the case for participants that are subject to a within-subjects design. On the one hand, this type of hypothesis is applicable when one wants to compare the different investment and mark-up choices for the different compositions of the opponents, previously referred to as the subgame. Do participants enter other numbers when they would play against inexperienced or experienced players? On the other hand, this approach is also applicable when one compares the strategic behavior in the low-risk and the high-risk setting, since in each session subjects are playing both a low-risk as well as a high-risk treatment. As a result, we are dealing with paired observations. Instead of using the parametric paired t-test, we opt for the *paired-sample Wilcoxon signed rank test*.

Lastly, the experiment also wants to compare the behavior with respect to the different sessions. From this session perspective, we have a between-subjects design, because the samples are independent. These hypotheses answer the question whether the input data in the different sessions come from the same underlying data structure. The most common statistical test to compare two independent samples is the *Mann-Whitney U test*, also referred to as the *Mann-Whitney Wilcoxon test*.

All tests have been executed in a subgame-by-subgame (i.e., comparing two samples pair-wise for each equivalent combination of experience levels like comparing a subgame I/I in a 2/1/L and a 2/1/H treatment) or scenario-by-scenario analysis (e.g., comparing the input in a 2/1/L scenario for playing against opponent I on the one hand and opponent E on the other hand). Due to the limited number of observations, it could be difficult to significantly support or reject the expectations. Therefore, also aggregate analyses are executed. The respective p-values are consistently reported between brackets.

#### *7.1.4.3 Participant's play versus equilibrium play*

The parameter settings and treatments that have been described in Section 7.1.2 have been implemented in the PPP computer model with a continuous set of investment and mark-up percentages of Chapter 6. The resulting equilibrium strategy for a player, for each of the possible subgames in a particular treatment is found in Table 7.3, Table 7.4 and Table 7.5. Also the expected pay-off in equilibrium is reported. Moreover, the tables summarize the average play of the participants in the selected periods (discussed in Section 7.1.4.1). Note that these averages are just reported as a matter of comparison, but formal (non-parametric) statistical tests are required to present robust insights.

| | | | Experiment | | | Nash equilibrium | | |
|---|---|---|---|---|---|---|---|---|
| Treatment | Experience | Competition | Investment | Mark-up | Pay-off | Investment | Mark-up | Pay-off |
| 2/1/L | I | I | 2.50% | 13.63% | -7,367 | 2.23% | 23.72% | 51,049 |
| | | E | 2.31% | 13.57% | -239 | 2.04% | 19.59% | 22,902 |
| | E | I | 2.03% | 14.58% | 10,312 | 2.75% | 22.15% | 59,328 |
| | | E | 1.91% | 14.16% | 26,272 | 2.66% | 16.33% | 23,417 |
| 2/1/H | I | I | 2.76% | 19.94% | 16,296 | 3.94% | 26.50% | 40,307 |
| | | E | 2.79% | 17.75% | -3,026 | 3.81% | 22.33% | 13,137 |
| | E | I | 1.85% | 16.72% | 36,046 | 4.41% | 24.75% | 46,663 |
| | | E | 2.58% | 15.31% | 30,743 | 4.38% | 19.09% | 13,080 |
| 2/C/L | I | I | 2.24% | 14.89% | -1,751 | 3.14% | 24.84% | 55,197 |
| | | E | 2.24% | 12.96% | -10,251 | 3.05% | 20.56% | 26,954 |
| | E | I | 2.91% | 12.26% | 14,242 | 3.60% | 23.06% | 63,010 |
| | | E | 3.17% | 11.68% | 6,826 | 3.59% | 17.35% | 28,757 |
| 2/C/H | I | I | 2.72% | 17.99% | 14,786 | 4.79% | 28.05% | 52,362 |
| | | E | 2.27% | 18.62% | -18,701 | 4.72% | 23.92% | 26,100 |
| | E | I | 4.06% | 13.32% | 35,508 | 5.00% | 26.18% | 59,902 |
| | | E | 4.32% | 12.85% | 19,701 | 5.00% | 20.90% | 29,011 |
| 2/2/L[b] | I | I | 1.72% | 15.30% | 4,194 | 2.19% | 19.28% | 31,538 |
| | | E | 1.95% | 16.33% | -4,835 | /[a] | / | / |
| | E | I | 1.96% | 14.49% | 24,476 | / | / | / |
| | | E | 1.98% | 14.57% | 20,502 | 2.65% | 16.34% | 23,498 |
| 2/2/H[b] | I | I | 2.48% | 17.03% | -393 | 3.88% | 21.95% | 20,996 |
| | | E | 2.44% | 17.71% | -19,442 | 3.24% | 25.23% | 7,028 |
| | E | I | 2.94% | 17.32% | 26,979 | 4.77% | 24.02% | 62,903 |
| | | E | 2.87% | 16.89% | 19,745 | 4.38% | 19.11% | 12,678 |

Table 7.3 Equilibria and average play in the two-player treatments

[a]Refers to the fact that no convergence was found in the exact equilibrium calculation

[b]Only the strategies for the first project in the pipeline have been reported

| Treatment | Experience | Competition | Experiment: Investment | Experiment: Mark-up | Experiment: Pay-off | Nash equilibrium: Investment | Nash equilibrium: Mark-up | Nash equilibrium: Pay-off |
|---|---|---|---|---|---|---|---|---|
| 3/1/L | I | I/I | 1.69% | 13.96% | -24,156 | 0.97% | 21.68% | 17,381 |
| | | I/E | 1.52% | 14.60% | -17,495 | 0.00% | 25.62% | 11,543 |
| | | E/E | 1.43% | 15.51% | -21,257 | 0.00% | 47.67% | 200 |
| | E | I/I | 1.32% | 11.95% | -7,773 | 2.85% | 22.78% | 64,862 |
| | | I/E | 1.62% | 10.22% | -9,416 | 2.58% | 16.16% | 21,456 |
| | | E/E | 1.83% | 9.76% | -14,884 | 0.00%[1]<br>2.20%[2] | 23.60%[1]<br>15.61%[2] | 10,285 |
| 3/1/H | I | I/I | 1.98% | 15.89% | -23,226 | 2.80% | 25.05% | 1,547 |
| | | I/E | 2.10% | 14.75% | -30,368 | 0.00%[1]<br>3.40%[1] | 50.00%[1]<br>22.72%[1] | 14 |
| | | E/E | 2.02% | 19.28% | -37,548 | 0.00% | 50.00% | -7,690 |
| | E | I/I | 2.06% | 13.61% | -6,663 | 4.12% | 24.17% | 36,803 |
| | | I/E | 2.43% | 11.06% | -11,767 | 4.11% | 19.26% | 8,681 |
| | | E/E | 2.63% | 9.36% | -16,961 | 0.00%[1]<br>4.11%[2] | 50.00%[1]<br>19.17%[2] | 11,443 |
| 3/C/L | I | I/I | 2.55% | 14.17% | -9,337 | 2.25% | 21.32% | 13,621 |
| | | I/E | 1.95% | 14.47% | -14,510 | 1.66% | 21.52% | 3,911 |
| | | E/E | 1.75% | 15.25% | -18,012 | 0% | 50.00% | 60 |
| | E | I/I | 2.50% | 9.09% | -4,113 | 3.41% | 19.83% | 39,324 |
| | | I/E | 2.48% | 9.37% | -6,678 | 3.55% | 17.14% | 26,824 |
| | | E/E | 2.19% | 9.37% | -8,924 | 2.68% | 15.39% | 12,235 |
| 3/C/H | I | I/I | 2.57% | 22.72% | 866 | 3.99% | 24.76% | 6,967 |
| | | I/E | 2.46% | 21.11% | -19,756 | 3.57% | 25.04% | -2,940 |
| | | E/E | 2.38% | 22.52% | -20,398 | 0.72% | 50.00% | -6,850 |
| | E | I/I | 3.16% | 11.10% | 9,617 | 4.99% | 22.52% | 28,932 |
| | | I/E | 2.58% | 10.81% | 4,088 | 5.00% | 20.36% | 21,295 |
| | | E/E | 2.49% | 10.59% | 422 | 4.45% | 18.75% | -2,563 |

Table 7.4 Equilibria and average play in the three-player, single-project treatments

[1,2]Refers to the fact that there is an asymmetric strategy for the players with the same experience level. The superscript means that either one or two of the equivalently experienced players apply that particular choice.

| Treatment | Experience | Competition | Experiment: Investment | Experiment: Mark-up | Experiment: Pay-off | Nash equilibrium: Investment | Nash equilibrium: Mark-up | Nash equilibrium: Pay-off |
|---|---|---|---|---|---|---|---|---|
| 3/2/L | I | I/I | 2.37% | 14.29% | -21,885 | 0.00%[1]<br>1.30%[2] | 18.10%[1]<br>15.22%[2] | 1,858 |
| | | I/E | 1.82% | 14.56% | -13,670 | 0.00% | 23.77% | 5,813 |
| | | E/E | 2.04% | 15.71% | -18,939 | 0.00% | 40.07% | 95 |
| | E | I/I | 1.62% | 11.59% | 1,942 | 2.98% | 19.70% | 55,174 |
| | | I/E | 1.75% | 11.04% | 3,450 | 2.53% | 15.97% | 19,795 |
| | | E/E | 2.04% | 9.99% | -2,379 | 0.00%[1]<br>2.19%[2] | 23.58%[1]<br>15.61%[2] | 10,326 |
| 3/2/H | I | I/I | 2.35% | 17.21% | -33,089 | 2.73% | 20.65% | -10,293 |
| | | I/E | 1.89% | 19.01% | -33,810 | 0.00%[1]<br>3.22%[1] | 50.00%[1]<br>21.72%[1] | -3,855 |
| | | E/E | 1.52% | 20.71% | -22,455 | 0.00% | 50.00% | -7,710 |
| | E | I/I | 1.72% | 18.46% | 4,758 | 4.26% | 22.18% | 33,881 |
| | | I/E | 1.47% | 20.40% | 6,538 | 4.10% | 19.18% | 8,424 |
| | | E/E | 1.74% | 21.21% | 23,707 | 0.00%[1]<br>4.10%[2] | 50.00%[1]<br>19.20%[2] | 3,923 |

Table 7.5 Equilibria and average play in the three-player, two-project treatments

[1,2]Refers to the fact that there is an asymmetric strategy for the players with the same experience level. The superscript means that either one or two of the equivalently experienced players apply that particular choice.

The one-sample Wilcoxon signed rank test for each of the subgames compares the played equilibrium with the expected investment and mark-up choice. In the two-player setting, the alternative hypothesis that players tend to invest less than the choice that the equilibrium prescribes is confirmed in 82% of the total number of subgames. Mark-ups are significantly below expectation in 82% of the scenarios at a significance level of 10%. Instead of comparing each pair of observations separately, all results have been compared on a pairwise aggregated basis, confirming the underinvestment ($p=3.78*10^{-16}$) and underbidding ($p<2.2*10^{-16}$). The median of the gaps is a decrease in investment percentages of 0.96% and in the mark-up percentages of 6.86%.

In the three-player setting, the observations led to a different null hypothesis for experienced and inexperienced players. For inexperienced players, the null hypothesis that investments are equal to or smaller than the prescribed equilibrium is rejected in 61% of the individual subgames at a confidence level of 90%. Also in 61% of the subgames of experienced players, the opposite null hypothesis (i.e., that investments are equal or larger than the equilibrium) is rejected. Executing this statistical test on the aggregate results leads to the same observation: inexperienced players tend to overinvest ($p=7.8*10^{-7}$) and experienced players tend to underinvest ($p=1.8*10^{-10}$). For the mark-ups, the aggregate study clearly supports the underbidding behavior ($p<2.2*10^{-16}$), which is confirmed in the subgame-by-subgame analysis in 89% of the cases.

The large gaps in the realized pay-offs of the laboratory experiment with the expected pay-offs in equilibrium underline the consequences of the deviating strategic behavior. Nevertheless, the participants do outperform the theoretically expected pay-off in the E/E games of treatment 2/2/H and the E/E/E games of treatment 3/2/H. Could this be a "hidden collusion"?

Finally, there are some cases in which a player should stay out of the three-player market (i.e., no investment and a 50% mark-up) in the high-risk treatments. In practice, this almost never occurs. There were only seven out of ninety participants in the three-player treatments that decided to stay out of the market in at least one period. Nevertheless there are only two inexperienced players that consistently decided to not participate as described by the equilibrium in the high-risk settings when playing against experienced opponents. Moreover, Table 7.4 and Table 7.5 highlight that it is unsustainable to invite three bidders in the treatments 3/1/H and 3/2/H with all experienced players. One contractor should decide to stay out of the market. In the laboratory setting, this never occurred.

#### *7.1.4.4 Low-risk play versus high-risk play*

In each session, participants are subjected to both a low-risk treatment as well as a high-risk treatment. The Wilcoxon signed rank test for paired observations on a subgame-by-subgame level in two-player treatments reported a significant increase (confidence = 90%) in the investment levels in 58% of the subgames and an increase in mark-ups in 75% of the cases. The aggregated analysis rejects the null hypotheses that investments are equal or lower in the high-risk treatments than in low-risk treatments ($p=2.1*10^{-6}$) and an equivalent result with respect to the mark-ups ($p=5.4*10^{-7}$).

The subgame-by-subgame analysis for the same hypotheses are less outspoken for the three-player treatments, i.e., only significant results in 39% of the investment comparisons and in 44% of the mark-up comparisons. On an aggregate level though, we could conclude that, on average, investments and mark-ups tend to be higher in high-risk treatments than in low-risk treatments ($p=2.5*10^{-4}$ and $p=2.1*10^{-10}$ respectively). The median of the investment increase is 0.27% and 3.26% for the mark-up increase.

#### *7.1.4.5 Subgame-dependent play*

The next step is to investigate whether the participants diversify their strategy over the different compositions of the competitors. In other terms, do they insert different figures in the respective investment input and mark-up input boxes of Figure 7.2. Looking at these dissimilarities from the theoretical Nash equilibrium angle, the differences are sometimes outspoken and sometimes quite subtle. Albeit a little bit simplistic, we could bluntly generalize the dynamics into the following statements. Firstly, lower investment ought to be expected when the opponents are more experienced. Secondly, the mark-ups are expected to be increasing for inexperienced players and decreasing for experienced players when the competitive position of the opponent(s) becomes stronger.

No straight line can be drawn by analyzing the scenario-by-scenario comparisons. While there seems to be a general tendency that is in line with the statements, statistical significance is often lacking as the impact is subtle. Admittedly, looking at the theoretical equilibria in the two-player settings, these investment differences are expected to be rather small. Interestingly, the empirical analysis does find significance for an opposite tendency, namely that an experienced player invests more when he plays against an experienced opponent ($p=0.04$). Moreover, that experienced player also requests a smaller mark-up ($p=0.05$).

While there is also no outspoken result in the scenario-by-scenario study, the aggregate three-player results point towards a decreasing investment when inexperienced players are playing against I/E ($p=0.03$) and E/E ($p=0.06$) relative to an I/I situation. The mark-up difference for inexperienced players is also significant in that case ($p=0.02$). The analysis for the experienced players did not significantly reveal these dynamics. In summary, while we expect players to tune their behavior with respect to the competitors, these tendencies are not always supported by the empirical evidence from the experiment.

#### *7.1.4.6 Session-dependent play*

Two governmental policies are tested in the experiment: the impact of a government reimbursement and the impact of an introduction of a second project. For the assessment of the latter policy, we only looked at the changes for the first tender in the pipeline. For the session comparison, the 2/1 and 3/1 treatments are considered as the baseline. The tested hypotheses are defined by the expected dynamics of the theoretical equilibria. As these dynamics are often depending on other variables, i.e., the project risk and the experience levels of the opponent(s), a subgame-by-subgame analysis is executed for the low-risk and high-risk settings separately.

*Two-player treatments*

The introduction of an investment reimbursement is expected to result in greater investment efforts, which is confirmed for experienced players in the low-risk setting ($p=0.05$ for play against I and $p=3.9*10^{-3}$ for play against E) and the high-risk setting ($p=3.9*10^{-3}$ for play against I or E). In the high-risk case, experienced players should move to the maximum investment level according to the theory and this is the case for 4 out of 15 participants in the selected periods. The mark-up influence tends to be limited in theoretical terms and also in the experiment, no strong dynamics are found, except for a mark-up decrease for the inexperienced players (p=0.08).

The introduction of a second project without spillover effects of the investments was expected to only create additional incentives for experienced players that face inexperienced players which is interestingly confirmed in the experiment (p=0.03). The inexperienced player in this particular subgame diminishes the investment effort (p=0.05). Concerning the mark-ups, the statistical tests were not able to reveal any dynamics.

*Three-player treatments*

The introduction of compensation could lead to higher investment efforts, which is the case in the low-risk setting if the inexperienced player faces I/I (p=0.05) and if the experienced player faces I/I (p=0.02) or I/E (p=0.05). In the high-risk case it is only the experienced player facing I/I who finds enough statistical significance for the investment effort adjustment in a positive direction. From a mark-up perspective, inexperienced players even increase the preferred mark-up. Also in the single-project setting of Chapter 4, we claim that reimbursements should amount up to 80% in order to trigger additional incentives. Additional sessions are required to assess this impact.

Last but not least, the introduction of the second project has mostly a mark-up impact, but not as expected. The mark-ups of the experienced players are significantly greater in the high-risk treatment of the two-project pipeline with respect to 3/1/H (p smaller than 0.01 for all subgames).

Comparing treatments is a daunting task and the previous analysis could not give us very clear insights into the overall dynamics, because of the limited number of independent observations. One divergent result is heavily penalized in the non-parametric test. Besides, the treatments are organized in different sessions and played by different cohorts. The impact of the group can highly influence the equilibrium convergence. Therefore, it is interesting to account for these group effects. As a result, the next section adventures to assume the parametric nature of the data and builds a linear mixed effects model.

#### *7.1.4.7 Linear mixed effects model*

The input data for the linear mixed effects model consist of investment and mark-up percentages from the five selected periods of all subjects. The data of the two-player treatments and the three-player treatments are split. Since we have different observations for each subject, we should account for the fact that these are panel data. Moreover, the non-parametric tests do not account for intra-group variability. Consequently, a mixed effects model is developed with the variable “subject”, referring to the identification number of the participant, and the variable “group”, referring to the identification number of the cohort as random effects. The fixed effects in the model are the player’s experience level (i.e., the variable “exp”), the experience vector for the opponents (i.e., the variable “opp”) and a factor variable that refers to the specific treatment (i.e., the variable “tr”). Furthermore, including the first-order interaction effects improves the Restricted Maximum Likelihood, so that these effects are also added to the mixed effects model. Conceptually, the model is defined as follows:

Investment ~ exp + opp + tr + exp * opp + exp * tr + opp * tr + (1|subject) + (1|group)

Mark-up ~ exp + opp + tr + exp * opp + exp * tr + opp * tr + (1|subject) + (1|group)

with the following codification in the two-player model (Table 7.6):

- “exp” is the experience level of the participant (0 = “inexperienced”, 1= “experienced”);
- “opp” is the experience level of the opponent (0 = “inexperienced”, 1 = “experienced”);

- "tr" is the treatment identity (t1 = 2/1/L, t2 = 2/1/H, t3 = 2/C/L, t4 = 2/C/H, t5 = 2/2/L, t6 = 2/2/H);

and with the following codification in the three-player model (Table 7.7):

- "exp" is the experience level of the participant (0 = "inexperienced", 1= "experienced");
- "opp" is the experience factor for the opponents (opp1 = "I/I", opp2 = "I/E", opp3 = "E/E");
- "tr" is the treatment identity (t7 = 3/1/L, t8 = 3/1/H, t9 = 3/C/L, t10 = 3/C/H, t11 = 3/2/L, t12 = 3/2/H).

| | Investment | | Mark-up | |
|---|---|---|---|---|
| Random effects | Variance | Std. Dev. | Variance | Std. Dev. |
| subject | 0.66611 | 0.8162 | 22.352 | 4.728 |
| group | 0.01827 | 0.1352 | 2.887 | 1.699 |
| Residual | 1.31959 | 1.1487 | 33.207 | 5.763 |
| # observations: 1800; # subject: 90; # group: 15 | | | | |
| Fixed effects | Estimate | t-value | Estimate | t-value |
| Intercept | **2.55920** | 10.279 | **13.62468** | 8.762 |
| exp | -0.52453 | -1.586 | 0.96758 | 0.517 |
| opp | **-0.30227** | -2.110 | -0.04189 | -0.058 |
| t2 | 0.08173 | 0.503 | **6.26737** | 7.691 |
| t3 | -0.32277 | -0.922 | 0.82927 | 0.379 |
| t4 | 0.04360 | 0.125 | **4.54073** | 2.073 |
| t5 | **-0.73190** | -2.091 | 1.81540 | 0.829 |
| t6 | -0.01000 | -0.029 | 3.58437 | 1.636 |
| exp*opp | **0.23733** | 2.191 | -0.39782 | -0.732 |
| exp*t2 | -0.15653 | -0.834 | **-4.09913** | -4.356 |
| exp*t3 | **1.20580** | 2.614 | -2.72280 | -1.041 |
| exp*t4 | **2.10733** | 4.560 | **-5.98547** | -2.288 |
| exp*t5 | 0.54260 | 1.176 | -2.05507 | -0.785 |
| exp*t6 | 0.85040 | 1.843 | -1.03833 | -0.397 |
| opp*t2 | **0.57480** | 3.064 | -1.05287 | -1.119 |
| opp*t3 | 0.31420 | 1.675 | -1.01427 | -1.078 |
| opp*t4 | 0.08760 | 0.467 | 0.31893 | 0.339 |
| opp*t5 | 0.31060 | 1.656 | 0.79560 | 0.845 |
| opp*t6 | 0.12320 | 0.657 | 0.36660 | 0.390 |

Table 7.6 Linear mixed effects model for two-player treatments

| | Investment | | Mark-up | |
|---|---|---|---|---|
| Random effects | Variance | Std. Dev. | Variance | Std. Dev. |
| subject | 0.9123 | 0.9551 | 26.3726 | 5.1354 |
| group | 0.0260 | 0.1613 | 0.5387 | 0.7339 |
| Residual | 1.4229 | 1.1929 | 40.6828 | 6.3783 |
| # observations: 2700; # subject: 90; # group: 15 | | | | |
| Fixed effects | Estimate | t-value | Estimate | t-value |
| Intercept | **1.61290** | 5.712 | **14.44036** | 9.611 |
| exp | -0.21527 | -0.578 | -2.97166 | -1.486 |
| opp2 | -0.08141 | -0.547 | -0.28568 | -1.486 |
| opp3 | -0.11876 | -0.798 | 1.03792 | 1.305 |
| t8 | **0.36593** | 2.301 | **2.41749** | 2.843 |
| t9 | **0.88622** | 2.234 | -0.67047 | -0.318 |
| t10 | **1.24209** | 3.131 | **7.57569** | 3.589 |
| t11 | 0.65100 | 1.641 | -0.05027 | -0.024 |
| t12 | 0.68789 | 1.734 | 2.33538 | 1.106 |
| exp*opp2 | **0.29096** | 2.587 | -0.52558 | -0.874 |
| exp*opp3 | **0.49031** | 4.360 | **-2.70664** | -4.501 |
| exp*t8 | 0.29640 | 1.864 | -1.25004 | -1.470 |
| exp*t9 | 0.26356 | 0.509 | -1.30613 | -0.469 |
| exp*t10 | 0.23062 | 0.445 | **-7.23858** | -2.599 |
| exp*t11 | -0.32067 | -0.619 | 0.06813 | 0.024 |
| exp*t12 | -0.32018 | -0.618 | 5.09498 | 1.829 |
| opp2*t8 | 0.18140 | 0.931 | -1.29547 | -1.244 |
| opp3*t8 | 0.17787 | 0.913 | -0.11433 | -0.110 |
| opp2*t9 | -0.37207 | -1.910 | 0.83520 | 0.802 |
| opp3*t9 | **-0.67993** | -3.491 | 0.99407 | 0.954 |
| opp2*t10 | **-0.40473** | -2.078 | -0.40200 | -0.386 |
| opp3*t10 | **-0.55207** | -2.834 | -0.03840 | -0.037 |
| opp2*t11 | -0.27660 | -1.420 | 0.40927 | 0.393 |
| opp3*t11 | -0.08067 | -0.414 | 0.22367 | 0.215 |
| opp2*t12 | **-0.41460** | -2.128 | **2.41573** | 2.319 |
| opp3*t12 | **-0.52773** | -2.709 | **3.43533** | 3.298 |

Table 7.7 Linear mixed effects model for three-player treatments

The regression output shows that the introduction of the subject-specific random effect adds to the explanation of the variability. Comparing the two-player and three-player setting reveals that dynamics differ. The response to the bid reimbursement are for instance stronger in the three-player setting. In the two-player treatments, the competitive position significantly influences the investment responses, but in the three-player environment, this is also the case for the mark-ups. The increased mark-ups that are due to the greater risks, however, are mostly applied by inexperienced players in both sets of experiments. The introduction of a second project does not really result in significant strategic turnarounds according to the mixed effects model. A comparison of the two tables indicates that, on average, the bidding behavior differs in a two-player setting or a three-player setting. On average, investment efforts are lower in more competitive environments but the introduction of a compensation (treatments 9 and 10) helps to bridge this gap to a certain extent. Albeit a little bit daunting to assume normality of the data, this linear mixed effects model succeeds in better isolating the effects and including the interactions, which was hardly obtainable in the non-parametric analyses.

These regression results prove that policy assessments need to be seen in perspective as their success is impacted by the contingencies of the project and by the experiential parameters of the bidder and the opponents.

### 7.1.5 Discussion and conclusion

This first practical study is an attempt to verify how students, that are familiar with probability theory and equilibrium concepts, respond to risky bidding situations. It is definitely clear that participants consistently underbid which could therefore lead to negative pay-offs. This is especially the case in three-player settings. Eventually, this finding is in line with earlier auction studies (e.g., Engelbrecht-Wiggans et al. 2007)

The PPP market is very competitive and is subjected to the secrecy of bidding and cost data. The experiment aims to reveal as little pay-off information as possible to the participants, which reflects practice. Bidders only receive real cost information if they won a project. The winner’s curse was mostly apparent in the three-player treatments. It seems that bidders preferred to take risk in order to receive real cost information instead of mitigating the risk. Inviting three bidders in high-risk projects is often unsustainable, but only few participants consistently stayed out of the market. In practice, this could lead to inefficient tenders and unfavorable social equilibria.

Not all dynamics that were predicted by theory have been validated, but there is a clear response to changing risks and in general it are mainly the experienced players who respond to the introduction of government incentives. This supports the managerial insight that governments should beware of the danger that incentive creation mechanisms inflate the undue difference in experience levels. Besides, although the responses of practitioners could differ, one should still account for the fact that a determined willingness to win could lead to dangerous situations in which contractors with insufficient financial capabilities could go into default.

From a methodological perspective, this section offered some modelling guidelines that could be applied in a wide range of settings. The setup considers a carefully designed procedure to avoid collusion and learning effects that could lead to biased effects. The test of this setup could pave the way for further laboratory studies in fields that are suffering from a lack of empirical data.

## 7.2 The practitioner's perspective

The outcomes from the previous section stem from a laboratory experiment played by students that are familiar with probability and risk management concepts, but who are often not aware of the traps and challenges of PPP procurement. Nevertheless, the results gave an insight into how human dynamics might not be in line with expectations from theory.

In this section, we turn towards the practitioners. Assumptions needed to be made in order to build the model, taking into account the trade-off between analytical manageability and the trustworthy representation of complexity. The models have led to results and policies, but so far the triangulation of these results has been left at the surface. This is the time at which the extensive modelling draws back to its practical application: the real world of public-private partnerships.

Along the course of the project, a research network has been established for model building and assumption triangulating purposes. Moreover, in a later stage of the project, intermediate findings have been discussed with a number of international contracting companies, Belgian and Australian public institutions and a set of advisory firms. The purpose of this section is to present how the conclusions from this dissertation are put in perspective from a practitioner's point of view and how the results are confirmed or nuanced by experience from practice. The subsequent sections cover the main themes that have consistently been covered in the previous chapters: the competitive environment, the project risk and the two government intervention mechanisms, namely the research cost reimbursement and the project agenda.

It is outside the scope of this dissertation to give a full empirical analysis of the current market and about the tendering strategies of consortia or public institutions. We endeavored to gather bidding data, but the highly competitive and immature nature of the PPP market inhibits to retrieve these very sensitive data. Nevertheless, attempts are currently made by European research networks to assemble a market overview based on case studies. Unfortunately, what is really living within the consortia from a strategic angle will always be hard to unravel.

This section discusses some important feedback from a selection of the interviewees (Table 7.8). Opting for a multi-faceted and multi-stakeholder view, the selected respondents are recruited in developed and developing countries at the public and the contractors' side and among advisors of the middle field. However, since we only exhibit a few opinions, it should be clear that these views are not generalizable. The country-specific and project-specific peculiarities inhibit imposing an all-embracing view on the theoretical findings. The interviews with the practitioners had a semi-structured, open-ended nature based on a predefined list of themes.

| Respondent | Function | Region of expertise |
|---|---|---|
| A | Partnerships Victoria | Victoria (Australia) |
| B | Manager at Department of Treasury & Finance South Australia | South Australia (Australia) |
| C | Executive director of investment company | Australia and other developed countries |
| D | PPP project coordinator | Chile |
| E | Independent PPP consultant | Czech Republic |
| F | Independent PPP consultant | South Africa |
| G | Principal at infrastructure advisory service provider | Developing countries |
| H | Director at advisory firm | Belgium |
| I | Advisor in research and advisory institution for construction sector | Belgium |
| J | Partner at consultancy firm | Australia |
| K | Construction lawyer | Australia |
| L | Lawyer (public law) | Belgium |
| M | Independent legal PPP consultant | Europe |

Table 7.8 List of respondents

### 7.2.1 The competitive environment

The PPP bidding environment, which consists of the number of prequalified bidders and their respective experience levels, plays a significant role in the determination of the strategy equilibrium. This is especially driven by the bidding costs that are peculiar for PPP tenders. These costs consist of design, consultancy and legal fees, but also the consortium’s working cost. The investment costs in example cases amount easily up to two million euro for large Belgian projects (respondent L) and even 20 million dollar for mega-projects in Australia (respondent K). Respondent G experienced intrinsically attractive projects in the port and power sectors with fairly low bidding costs relative to the rewards of winning, while they are high in rail projects that are subject to market risk, attracting far less bidders.

As bid costs could become a burden for consortia, the theoretical results claim for a clear funneling principle. Neither the government nor the contractors benefit from an environment where four or more contractors are invited for the tender when considerable investments are required. The results show that strategic behavior is close to being levelled in the two-player environment, so that this automatically leads to more competition in the investment choice. Nonetheless, the results regularly identify soaring mark-ups. This seems counterintuitive for the public sector (respondents A,B), because they expect fierce price competition because of higher winning probabilities.

Alternatively, governments might fear for oligopolistic mechanisms and prefer three-player environments in order to increase competition and reduce the government cost (respondent A). The results agree that mark-ups will be lower, but they also state that, especially in markets with large gaps in the experience levels, the entrant will face a low probability of winning and will therefore not be enthusiastic to put a lot of effort in the bid preparation. Chapter 6 even claimed that it could be unsustainable to invite more than two bidders for a high-risk project. Nonetheless, the majority of example cases are characterized by a three-player prequalification while a two-player setting could be socially optimal. Respondent C, from a private sector perspective, acknowledges that one should favor a limited number of bidders for complex projects, but not for less complex projects.

Nonetheless, the theory states that entrants in the market will suffer from their disadvantageous position in relation to well-established firms. However, respondent D acknowledges that firms are reluctant to invest in bid preparation if they are not rewarded for the effort. The amount of investment should be positively correlated with the weight of the quality aspect (i.e., the cost adjustment share $\beta_i$) in the selection process. Alternatively, a standardization of procedures could result in transferable investments, in line with the spillover model in Section

5.5. In this vein, pre-tender investment efforts are not sunk in case of a loss, but the knowledge may be utilized in later tenders (respondent A).

The models reveal that opportunistic behavior has a heterogeneous nature in the three-player case: incumbent firms might use their experience advantage as a motive to request higher mark-ups, while inexperienced players tend to be averse for losing the upfront investments and in general initially apply higher mark-ups, while the investment is only considered in a second instance. Respondent C, an established player in his less competitive local market, has experience in coping with highly competitive heterogeneous market environments. When they first entered the international market, a lot of upfront consultancy costs were spent to offset their competitive disadvantage since they were not familiar with the jurisdiction. These high investment requirements serve as barriers for entry and are often perceived as an advantage for bigger companies with robust financial backgrounds (respondent E). Markets are different in this respect as the Canadian, for instance, is very competitive and efficient (respondent C), while Belgium, despite sufficient interest, usually attracts the same bidding audience (respondents H,L).

If a market gets mature and narrow, one might expect soaring government costs, but only respondent K claimed that Australian construction costs are escalating at a rate above the inflation rate. The other governmental and consultancy respondents believe the project costs for the government remained stable regardless of inflation and the increased financing cost after the financial crisis. Possible explanations could be that the final stage of maturity has not yet been reached and that governments and consortia benefit from learning effects and efficiencies and the increased ability of more accurately estimating working costs (respondent G).

### 7.2.2 The project complexity

In this dissertation, the complexity of the project is expressed as a single risk measure to model the uncertainty in the revenues and costs of the agreement. In contrast to former PPP literature, the model studies the impact of risk allocation in a competitive environment. Transferring uncontrollable risk is expensive. Supported by the argument that a project becomes troublesome once the contractor faces difficulties, contractors require high compensations for the transfer of tricky risks like the demand risk and permits risk (respondent E). Surprisingly, the political instability in a developing country like Nigeria makes port and energy projects financially very attractive because of the inefficient public sector alternative (respondent G).

On the other hand, the bidder should deal with the controllable risk like the operational risk and the capital expenditure risk. Low-risk projects with a repetitive nature like sewage infrastructure and social housing projects usually require less upfront investments (respondent K). Instead, inexperienced players will play on their mark-ups and will try to be the cheapest in order to obtain a position in the market and not necessarily by investing more upfront (respondent C).

The dynamics of the analytical results change when projects are more complex. In mature markets, experienced players are eager to invest in pre-tender research and the competitive mechanism is working well so that qualitative bids ought to be expected. Respondent H supports that contractors are keen to take up risks, because if these are managed well, the project allows for considerably higher profits compared to classic building projects where margins are under pressure. In a heterogeneous market, the results show the skepticism of inexperienced contractors to run the risk of losing high investments. When an inexperienced player faces at least two incumbents, he could leave the deal. All practitioners agreed that incentive mechanisms need to be considered to increase competition.

### 7.2.3 Government reimbursement

The theoretical results in the different chapters show that the impact of compensations is limited when two players are invited for tender, but becomes successful in a three-player environment. According to the low-risk project results, bidding strategies are not very diverse conditional on the experience levels and compensations should amount up to 80 or 90% so as to result in higher investments. A government compensation proves to give more prospering results for high-risk projects (without a pipeline). A partial compensation of 80% triggers proper incentives for both incumbents as well as entrants and their bidding strategies converge. It enables the willingness to invest and withholds a player from setting a high mark-up so that the initial heterogeneity becomes hazy and probabilities of winning get levelled. The respondents at the private side agree that compensations might work for complex projects (respondents C-M).

Less attractive projects could become more attractive when compensations are introduced and as a result, respondent K is in favor of compensations if it is impossible to attract two bidders without them. Respondent H refers to the Dutch market in which principally only two consortia kept interest as, together, they won all initial PPPs. The government restored other bidders' interest by compensating losing bidders. The reimbursements create a larger pool of capital that could benefit the market's attractiveness (respondent K). Another situation to reimburse investment efforts is when important informational or innovative added value can be created (respondent A). A major concern in that latter respect is to what extent the contractors should reveal their findings to the procuring government or to the general public. In low-risk projects, the compensations might trigger trial-and-error behavior and then they should only be applied if the market is still developing (respondents C,E).

In summary, respondent E believes in the threefold impact of bid compensations: more bidders will be attracted, bidding prices will be lower and it could enable smaller projects to be delivered by PPPs. Nevertheless, respondent J fears the undue difference in the treatment of bidders, so that strict limitations and guidelines are necessary. Anyhow, it is acknowledged that governments should first attempt to decrease the bidding costs (respondents K,M).

The views on the amount of compensation that will make a significant difference are diverse, ranging from 50% for respondent A to up to the entire reimbursement of prequalified SPVs in the South African context (respondent F). While compensations could have a large societal value because of the reduced renegotiation risk and the increased market competition, they come at a considerable cost in the short run. Awarding authorities do not always have the budget to offer sufficient compensations and often only attribute amounts that can barely cover the design costs (respondent L). Within the public entity, there is no real agreement between jurisdictions. Compensations range from zero to up to seventy or ninety percent in France and Canada (KPMG 2010). In the belief that competition for PPPs is still strong, South Australia does not have a policy of providing compensations for bid costs, preferring to determine this on a case by case basis, while neighboring state Victoria has a proactive policy of compensating to open up the market (respondent B). Because of the requirement of detailed design plans that would refrain potential bidders to participate, the Chilean government attributed compensations to the second and third runner-up, which resulted in more bids (respondent D).

### 7.2.4 The project pipeline

Markets significantly differ in their respective project pipelines. The pipeline approach that has been outlined in this dissertation has a more stringent nature than how pipelines are perceived in practice. For the purpose of the modelling, a pipeline was defined as a finite sequence of projects with an equivalent risk structure. In practice, this would mean that cost and income uncertainty are similar and the contractual arrangements are equivalent. Practitioners tend to broaden this understanding and consider a pipeline as a set of same-type projects (e.g., a pipeline of road infrastructure projects or a pipeline of sports infrastructure projects) or even a set of PPP projects in general. In this broader view, Canada has a reputation of keeping the market going, while the pipeline of the Private Finance Initiative in the United Kingdom dropped off (respondent C). In Australia, the state Victoria tries to maintain a pipeline and communicates the prospects of future opportunities when projects are launched, under the belief that a strong pipeline results in new competition and higher investments (respondents A, K). Respondents I and F, on the other hand, claim that it is not always evident to have a continuity of projects due to the magnitude of the budgetary requirements. Also the longevity of projects in combination with rapidly changing government structures do not benefit the feasibility of the pipeline. Eventually, respondent E claims that the number of projects should not exceed market capacity. An oversupply of projects could trigger cooperative bidding behavior or a lack of competitive eagerness.

The interviewed respondents are unanimously in favor of a project pipeline. The hypothesis claiming that investments would increase if a project pipeline is introduced could not be generally confirmed in the game-theoretic experiments. With respect to the results in Chapter 6 for instance, players with a competitive advantage invest slightly more in a two-project pipeline than when there is no pipeline. However, in the other cases, this could only occur if a spillover effect is present, i.e., if pre-tender investments still generate benefits later in the pipeline (Section 5.5). According to the respondents, however, a first advantage of the project pipeline is that it would definitely result in more investments in initial projects (respondents A,C,H,J,M) and that the total investment is spread over different projects (respondent K). The private sector is willing to invest more in non-project fixed costs and better plan its financial strategy (respondent E) and human resources can be employed for a longer time (respondent K). The experience of respondent A learned that consortia recently have a more consistent structure, apart from the financial partner. This means that consortia are entering different tenders with the same entities or companies (e.g., a particular dredging company that consistently collaborates with the same tunnel construction company). As a result, this steadiness reduces the start-up cost and other overhead costs for governing the stakeholders within the consortium.

Moreover, the government benefits from a pipeline because of the increased competition and the lower procurement cost which is in line with the experimental findings. Respondent C admits that the increased competition puts a ceiling on the contractors' profits in the longer run. Another downside is the danger of the so-called "lazy Susan" (i.e., the traditional Chinese turntable) approach in established markets: the work goes around and might be attributed to the desperate contractor (respondent C). Practitioners claim that the market sometimes settles a natural equilibrium. Contractors take into account "how busy" the competition is when they determine the bidding strategy. Often, consortia are not substantial enough to carry out more than two projects at the same time, so governments need to be conscious about the magnitude of the project and about spreading the work (respondent C,K). An alternative could be to split up large-scale infrastructure projects into a sequence of smaller projects. According to the theoretical results, this could lead to a more competitive tendering procedure. As a result, also small contractors, for whom the bid costs and the project budget requirements might become a financial burden, could benefit from entering the market. Of course, the project decomposition would only work to such an extent that it remains feasible or that no animosity among opposing consortia depraves the value of the project.

Since all respondents expect more competition and since the majority expects higher investments in the initial projects, all interviewees explicitly favor a long-term project pipeline over short-term bid cost compensations. Respondent M stipulates that pipelines will be better to attract overseas contractors, but respondents A and C claim that the pipeline should be visible and trustworthy. Nevertheless, as has been shown in Section 7.2.3, respondents still believe in the applicability of compensations.

### 7.2.5 Conclusion

Practitioners can share interesting views on the topics that have been covered in this dissertation. This small sample of interviews emphasized the importance of the questions that are addressed in this research project. However, it is a challenge to find a compromise between the multi-faceted PPP domain and an abstract modelling framework.

Most insights from the dissertation could find resonance among the practitioners. The insights concerning complexity and the impact of the procurement cost are in line with the practitioner's upfront expectations. However, also new insights on the investment-related dimensions and the incentive creation capability of government reimbursements found resonance. Especially the interplay of project risk and the composition of the bidding consortia (i.e., the number of players and their heterogeneity) add value to the practitioner's views on PPP procurement. Nonetheless, this section once again underlines the diversity in markets and jurisdiction-specific views and policies. Unfortunately, the practitioner's views originate from mother wit, expectations and guesswork without a quantitative, objective soundness.

# Chapter 8 Conclusions and future research

This final chapter serves as a wrap-up of what has been studied in this dissertation. It also recapitulates the limitations of the research, that immediately pave the way for new research opportunities. The research project instigated from a need to offer new theoretical approaches to model the tendering procedure in public-private partnerships. PPPs have gained importance in developing and developed countries. However, data are hard to obtain and the high-risk environment raises new challenges for both the public as well as the private sector, that are, if not managed properly, open sesames for disastrous project outcomes.

The objective of the dissertation was to model the PPP tendering procedure from the contractor's perspective and to subsequently assess governmental policies to ensure the competitiveness of the market. In a competitive format, each interested contractor optimizes his strategy which is composed of how much money he will invest in upfront research and which mark-up is appropriate in order to maximize the expected pay-off. At this lower level, the contractors converge towards a Bayesian Nash equilibrium. At the upper level of this bi-level programming-like model though, the public sector has the tools at hand to steer the procurement outcome. Governments are looking for the most advantageous proposal from a cost and quality perspective, but also consider the competitiveness of the market in the longer and shorter term. This has been studied in a single-project and multi-project setting. While a considerable number of insights were brought to the forefront along this dissertation, the next section summarizes the key takeaways.

## 8.1 Key takeaways from this dissertation

The different experimental and empirical results have led to quantitative and often abstract insights. The challenge lies in translating these results into straightforward policy measures that are founded by means of the methodologies of this dissertation. We distinguish the public scope and the private scope of the PPP.

### 8.1.1 The public sector's perspective

The government impersonates the architect of the tendering procedure and should take this assignment seriously. Since research costs for the contractors are high, the procurer should strive for a clear and efficient funneling principle. The contractors' expenditures should be predominantly postponed to the final bidding stages. Ideally, only two players are prequalified to move to the final bidding stage, because both will be incentivized to properly prepare the tender documents. However, governments might fear a reduction in the competitive powers. Alternatively, the model finds resonance to prequalify three bidders. In a low-risk setting this is certainly a cost-benefiting option, but in a high-risk setting, this could lead to a socially unsustainable situation. Empirically, prequalified contractors do not dispose of the bravery to withdraw.

Nevertheless, provided that sufficient incentives (i.e., research cost reimbursements) are introduced, three-player settings could function properly. It shows that compensations, if used in a smart sense, could close the gap between incumbents and newcomers. The experiments show that the compensations need to be close to the total investment expenditures. Of course, this would require clear guidelines to not overcompensate the bidders. This intervention might come at a cost in the short run, but could trigger the contractor's enthusiasm to enter the PPP market and preclude the contraction of the playing field in the long run.

Essentially, governments should focus on reducing non-value adding pre-tender costs for the consortia. This statement pleads for a standardization of contracts and contracting procedures and a reduction of exuberant project requirements.

Standardization might of course inhibit the flexibility and freedom of the contractors, so the standardization should not obstruct the creative and innovative process of the contractors. Nevertheless, reducing the investment needs and some parameters that unnecessarily add complexity to the project has a short-term beneficiary impact from a mark-up perspective and a long-term consequence in terms of the competitiveness of the market. Additionally, standardization could also make project-specific investments transmissible to future projects in the case of a project pipeline.

Chapter 5 and Chapter 6 introduced the concept of a pipeline of projects which serves as a government's project agenda. The theoretical results and the vision of practitioners both reveal the positive aspects of this pipeline. Contractors are better able to spread out budgets and risks over a prospect of projects, which would lead to a decrease in the government procurement cost and which would attract more international bidders on the long term. The impact of one additional project is already sufficient to create significant incentives. Therefore, it is in the public's interest to maintain and cement a short-term pipeline to keep on drawing the attention of the contractors. Besides, governments could also benefit from splitting up large and complex projects into smaller sub-projects if no coordination issues would arise. However, the theory could not find evidence in all scenarios that the pipeline creates a levelled playing field and attracts newcomers, which means that additional incentive creation mechanisms are certainly not otiose.

### 8.1.2 The private sector's perspective

Look before you leap into marriage is not only an appropriate warning for the government, but is also true for the private sector. Consortia should beware of entering the deal, as it can be a long and expensive process without any guarantees for success. Even once granted the project, the risky envelopment can lead to the disheartening winner's curse. Consortia need to be financially capable of performing the contracts and a careful mitigation of the risk is appropriate. As a consequence, it was shown that, even though being pre-qualified, contractors might benefit from refraining to continue the bidding process in high-risk environments, unless if additional government incentives are involved in the deal.

In this sense, the practice of underbidding was emphasized in Section 7.1. Since experiences are limited and the contracts require the utilization of considerable resources, default might be problematic, both for the contractor as well as for the society in general. Mark-ups should be appropriately reflecting the expected risk that cannot be accounted for by investing in research efforts.

These research efforts also deserve attention from a practical point of view. The bidding models propose equilibria that actually prescribe not to invest a lot in pre-tender research, especially as an inexperienced player. This might sound counterintuitive, but that could be partly attributed to the fact that the government decision mechanism was mainly focused on the bid price. Nevertheless, the equilibria advise incumbent players in a heterogeneous market to usually invest more to stay ahead of the newcomers. Consequently, the interaction between the expected investment efforts and the competitive environment was consistently significant. Instead of only assessing the need for investment based on the project's complexity, a consortium should also account for the competitive forces.

Finally, contractors would benefit from making the bid preparation efforts transferable to multiple projects. Establishing a consortium typically requires large start-up and overhead costs. Stable consortia and internal knowledge management diminish the necessity of project-specific pre-tender costs.

The majority of these findings stem from theoretical results under particular model assumptions and practical insights that were revealed during the research journey. Nevertheless, we believe that the model serves as a sounding board to initially assess the effectiveness of governmental policies. However, the rationality assumption that makes modelling feasible is often violated. Country-, project- and consortium-specific elements should always be incurred to make optimal PPP decisions.

## 8.2 Future research opportunities

The models that have been presented are subject to limitations that offer new research questions. We opted for a representative approach that closely mimics reality. Nevertheless, relaxing some of the model assumptions that have been introduced in Chapter 3 could disclose additional dynamics that approach reality better. This section elucidates four interesting research journeys.

### 8.2.1 Resource constraints

First of all, the models assume that the contractors have unlimited resources to bid on and to execute the projects, while the practitioners of the qualitative study in Section 7.2 claim that it is often impossible as a contractor to engage in more than two projects. The tendering process is time-consuming and the execution of projects requires a lot of resources. Therefore, resource constraints for the contractors ought to be introduced. A contractor usually has to make an allocation of monetary and physical resources over different activities. Moreover, a contractor's financial position is influenced by its history based on the total research cost that has been incurred for past tenders and the financial development in terms of profit and loss of the projects for which it was appointed the preferred bidder. The resource constraints are expected to render important repercussions on the bidding strategies of the contractors.

Nevertheless, its introduction poses important challenges for the modelling. Since the model needs to keep track of the resource position of the contractors, the number of additional state variables could skyrocket. Relying on a monetary constraint could be challenging, but in a simplified manner, it could be a convenient approach to cap the number of projects that a consortium is able to execute.

In line with the auction and procurement literature that does include capacity constraints, one could expect fiercer competition and more aggressive bidding earlier in the pipeline. Later in the pipeline, greater mark-ups and lower investments could be expected because of the reduced competition. This would then support the analogy with the "lazy Susan" (Section 7.2.4) and projects are naturally attributed to the contractors that have sufficient capacity. Moreover, we intuitively expect that the budget constraint will be proven to be another inhibitor for inexperienced contractors to enter the PPP market. Contractors will try to avoid default and might limit their expenditures early in the project pipeline. Therefore, the intervention of the government could be of paramount importance to open up the market and close the gap between incumbents and entrants.

### 8.2.2 Randomly arriving contractors and projects

In the current models, the pipeline of projects was fixed and commonly known. Also the number of bidders and their identity remains constant along the pipeline. In fact, the project characteristics and bidding environment characteristics are exogenously set. Adding the possible entry of new projects or adding the feature that a contractor may face different opponents for each project, adds complexity to the model. This is mainly due to the fact that the PPP model considers heterogeneity in the contractors' experience levels. In a fully dynamic setting, one needs to include a probability for each possible scenario (or subgame) that may occur in the future. Therefore, we need entry probabilities or the probability that a player may be prequalified.

To illustrate, in the current two-player setting with two players and initial experience vector (0,2), we only need to consider the experience vectors (2,2) and (0,4) for the second project. If two players are prequalified in a two-project setting with randomly arriving bidders, one needs to investigate each possible outcome. On the one hand, if one would win the first project, one will take into account the occurrence of the subgames (2,0), (2,2), (2,4), (2,6), (2,8) and (2,10) for the second tender. On the other hand, if one loses the first project, the probabilities of subgames (0,0), (0,2), (0,4), (0,6), (0,8) and (0,10) need to be included.

At first sight, the impact of allowing other consortia to enter the project pipeline would be expected to be highly dependent on the experience level of the contractor under study and on the experience levels of the opponents. Hence, defining a hypothesis on this matter could be perilous. However, if we would only allow for the arrival of new entrants, one might expect contractors to safeguard the competitive position as soon as possible, resulting in more competition. Also the pipeline itself could have a more randomized feature in the sense that projects arrive with a particular probability. Moreover, the current multi-project settings assumed stochastically equivalent projects, but also this assumption could be relaxed, which would render a methodological turnaround.

### 8.2.3 Model parameters

The previous extension relates to the multi-project setting, but also each individual project is subject to assumptions. First of all, the government compensation mechanism that has been implemented compensates all losing bidders with a predefined fraction of their research cost. This entails some consequences: the contractors need to prove the pre-tender expenses and also underperforming contractors receive an equivalent reimbursement fraction. Other mechanisms could be investigated, like only compensating the second best bidder or letting the fraction depend on the ranking of the bid.

Secondly, the impact of experience and investment was assumed to be uncorrelated. Nevertheless, in some markets, it could for instance be the case that experienced bidders more adequately utilize investment efforts. This would mean that the covariance between pre-tender research and a consortium’s experience needs to be contained within the model.

### 8.2.4 Opportunities for related disciplines

This research topic and the methodology that is outlined in the dissertation are on the verge of a wide spectrum of research fields. The manageability of the study required a compromise with each of the interrelated fields.

With regard to the operations research experts in algorithmic game theory, the equilibrium heuristics are an opportunity for further improvement. The purpose of the dissertation lies in gaining important insights from a flexible theoretical study in a relevant business context. We managed to uncover important general bidding dynamics, but a detailed study that overcomes for instance computation time issues and convergence problems requires additional efforts.

With respect to the economists and the analytical game theory and auction theory specialists, the research managed to apply the essential concepts that these respective fields have to offer. The analytical closed-form expressions and mathematical proofs were subordinate to the practical application and the veracity of the models and findings.

The dissertation contributes to the construction infrastructure literature in general and to the academic PPP literature in particular. The PPP field has a merely empirical nature, but the theoretical model adds initial insights into a highly relevant topic that is difficult to study from an empirical angle due to the scarcity of data. The research track that this dissertation offers would benefit from scrutiny of past projects tenders in order to fully validate the modelling approach.

As a final remark of this work, the relevance of this topic and methodology do not necessarily need to stop at the boundaries of operations management. We believe that there are also important aspects of the PPP model that are applicable in other fields. The Research & Development research also deals with uncertain developments that require large upfront investments in a competitive context. Secondly, corporate finance could gain insights in the context of mergers and acquisitions. If these are organized in a competitive context, the acquiring corporations need to assess the resources to attribute to these procurement options while a lot of uncertainty exists in the bidding outcome and the profitability of the acquisition.

# Appendix A Definitions and notation

### Abbreviations & definitions

| | |
|---|---|
| Cohort | Refers to a group of participants in a laboratory bidding experiment. The players within a cohort interact with each other, but they do not interact with players from distinct cohorts. |
| Continuation value | Refers to the expected pay-off for the future stages of the stochastic game. Chapter 6 initially assumes that the continuation value beyond the communicated pipeline is zero. Section 6.5 relaxes this assumption and constructs an infinite stream of revenues. |
| CSM | Consistent strategy model: this approach is used in Chapter 5 and means that the *ex ante* investment and mark-up decision is the same for all the projects in the pipeline. |
| MPE | Markov perfect equilibrium, an equilibrium refinement concept that states that a strategy consists of state-dependent actions |
| Partial strategy | A partial strategy reflects the actions for a particular subgame. In the dissertation, a “strategy” actually refers to a partial strategy. |
| Pipeline | A sequence of similar-type PPP (sub-)projects in which the government engages in the near future |
| PPP | Public-Private Partnership |
| Spillover | Modification to the model that incurs that pre-tender investment for a particular project has a propagating effect in later tenders |
| SPV | Special purpose vehicle, the contractor’s consortium |
| Stage | The stage of the game in the context of this dissertation refers to the sequence number of the project of the pipeline. Consequently, a three-project pipeline consists of three stages. |
| State | The state variable in the context of Chapter 6 consists of an experience vector and the number of projects that are remaining in |

| | |
|---|---|
| | the pipeline. A Markov strategy relies on the concept of a state as this strategy prescribes an action for each state of the game. |
| Stochastic game | A finite or infinite dynamic game that is played by one or more players with probabilistic transitions between a finite number of states |
| Stochastically equivalent | Equivalence in the stochasticity: two projects are for instance stochastically equivalent if their *a priori* cost probability distributions (i.e., without considering experience or investment) have the same expected value and variance |
| Subgame | A game-theoretic concept that refers to a game within a game up to a particular point where the players know exactly where they are. A subgame in the dissertation's context refers to an experience vector. |
| Treatment | In Section 7.1, a combination of model parameters defines a treatment |
| VSM | Variable strategy model: this approach is used in Chapter 5 and means that the bidder will determine, *ex ante*, a specific investment and mark-up choice for each project separately in the pipeline, but this choice cannot be changed when new information becomes available later in the pipeline |

**Notation**

| | |
|---|---|
| $a^z$ | The action profile in stage $z$ of the stochastic game, that consists of the individual actions $a_p^z$ of the players |
| $A_p$ | The actual cost of the project, taking into account that player $p$ has won the tender |
| $\alpha$ | Spillover variable, the fraction of the investment that is transferable to the next project in the sense that it has an impact on the cost and knowledge outcome |
| $\mathcal{A}$ | Refers to the set of available actions |
| $b_p$ | Bid probability distribution for player $p$ and associated cumulative probability distribution $B_p$ |
| $\beta_e$ | Maximum disadvantage of a lack of experience |
| $\beta_i$ | Maximum disadvantage of a lack of investment |
| $c_p$ | Cost probability distribution for player $p$ |
| $\gamma_e$ | Maximum risk impact of a lack of experience |
| $\gamma_i$ | Maximum risk impact of a lack of investment |

| | |
|---|---|
| $d$ | Percentage fraction of the investment efforts that the government reimburses to losing bidders |
| $e_p$ | The experience level for a player $p$ |
| $E$ | The number of experience levels (=$e_u$+1) |
| $e_u$ | The number of experience intervals on the experience scale |
| $\theta^z$ | State variable in the sequential bidding model, a combination of the current experience levels and the number of remaining projects in the sequence |
| $\Theta^z$ | The set of available states in stage $z$ |
| $f$ | Vector of the players' average pay-offs $f_p(s\|e)$ that results from the simulation and that is an estimator for the expected pay-off $\pi$ |
| $g_p$ | Player- and strategy-specific direct cost impact that is expressed as a fraction that is applied to the (unknown) project cost |
| $h_z$ | The history variable that summarizes the information of previous tenders in the pipeline |
| $I$ | Total number of discrete investment levels |
| $i(.)$ | Investment percentage that is related to a particular strategy or action |
| $\lambda_e$ | Experiential learning rate |
| $\lambda_i$ | Investment learning rate |
| $M$ | Total number of mark-up levels |
| $m(.)$ | Mark-up percentage that is related to a particular strategy or action |
| $\mu$ | A scaling factor that equals the *a priori* expected actual cost and that is common for all bidders |
| $\mu_e$ | Experiential cost decrease rate |
| $\mu_i$ | Investment cost decrease rate |
| $P$ | The total number of players |
| $\pi$ | The pay-off vector that consists of all players' expected pay-offs $\pi_p$. It might consist of an instantaneous term and a continuation value. |
| $q_p$ | Probability of winning for player $p$ |
| $Q$ | The set of transition probabilities to move from one state to another state, given a particular action profile |
| $\rho$ | The instantaneous pay-off vector that consists of all players' expected pay-offs $\rho_p$. It consists of the stage-specific pay-off without taking into account future projects. |
| $s$ | A strategy profile $(s_1, s_2, \dots s_P)$ |
| $s^*$ | The equilibrium strategy profile $s^* = (s_1^*, s_2^*, \dots, s_P^*)$ |

| | |
|---|---|
| $(s\|e)$ | Strategy profile $s$, given the experience vector $e$. Typically used in combination with a probability or a pay-off calculation |
| $s_p$ | A strategy for player $p$ |
| $s_{-p}$ | A strategy vector for the opponents of player $p$ |
| $s_p^z$ | The decisions within strategy $s_p$ that are specific for project (or stage) $z$ |
| $S$ | Set of available strategy profiles, for which $S_p$ thus refers to the set of available strategies for player $p$ |
| $\sigma$ | Uncontrollable risk parameter |
| $\sigma_p$ | Experience- and investment-specific standard deviation that is expressed as a fraction of the actual (unknown) project cost. It is also referred to as the controllable risk parameter. |
| $\mathcal{V}$ | The continuation value that reflects the expected pay-offs for the future stages of the stochastic game |
| $Z$ | The number of projects in the pipeline |

# Appendix B Pseudo code algorithms

**Code strategy game algorithm (Chapter 4 & Chapter 5)**

ALGORITHM 1: StrategyGame$(p, e)$
$k_2$ = number of strategy game iterations
**for all** $y \neq p$ **do**
    HomogeneousGame$(y)$
    HeterogeneousGame$(y)$
**end for**
**for** $i = 1$ to $k_2$ **do**
    **for all** $y \neq p$ **do**
        Select $s_y \in R_y$ randomly
    **end for**
    **for all** $x_i \in S_p$ **do**
        $s \leftarrow (s_1, \ldots, s_{p-1}, x_i, s_{p+1}, \ldots, s_P)$
        CalculatePayoff$(e, s)$
        $F(x_i) \leftarrow F(x_i) + f_p(s|e)$
    **end for**
**end for**
$s_p^* \leftarrow$ argmax $\{F(x_i), \forall i\}$

ALGORITHM 2: HomogeneousGame$(q)$
$rds$ = number of rounds
$e' \in \mathbb{R}^P$
$e' \leftarrow (e_y, e_y, \ldots e_y)$
$s' \in \mathbb{R}^P$
$t \in \mathbb{R}^{P^r}$
**for** $i = 1$ to $P^{rds}$ **do**
    Select $t_i \in S_y$ randomly
**end for**
**while** $rds > 1$ **do**
    **for** $i = 1$ to $P^{rds-1}$ **do**

$s' \leftarrow (t_{(i-1)*P+1}, \ldots t_{(i-1)*P+P})$
CalculatePayoff($e', s'$)
$t_i \leftarrow$ argmax $\{f_p(s'|e'), \forall p\}$
**end for**
$rds = rds - 1$
**end while**
$(t_1, t_2, \ldots, t_P) \rightarrow R_y$

ALGORITHM 3: HeterogeneousGame($q$)
$k_1$ = number of iterations
$n$ =number of shortlisted strategies
**for** $i = 1$ to $k_1$ **do**
**for all** $r \neq y$ **do**
Select $s_r \in S_r$ randomly
**end for**
**for all** $x_i \in S_y$ **do**
$s \leftarrow (s_1, \ldots, s_{y-1}, x_i, s_{y+1}, \ldots, s_P)$
CalculatePayoff($e, s$)
$F(x_i) \leftarrow F(x_i) + f_y(s|e)$
**end for**
**end for**
Sort$\left(S_y, F(x_i)\right)$
Best $(n - P)$ strategies $\rightarrow R_y$

**Code best response algorithm (Chapter 6)**

ALGORITHM 4: MainAlgorithm()
Generate $R$ random action profiles $a^r \in \mathcal{A}$ for $r \in \{1,2, \ldots, R\}$
for $r = 1$ to $R$ do
BestResponseAlgoritm($a^r$)
end for
EvaluateEquilibria()

ALGORITHM 5: BestResponseAlgorithm($a$)
$BRMAXREP$= maximum number of loops
$BRMINREP$= minimum number of loops
$conv$=convergence threshold
$Counter \leftarrow 0$
for $k_1 = 1$ to $BRMAXREP$ do
$o \leftarrow a$
for $p = 1$ to $P$ do
$a_{-p} \leftarrow a \setminus \{a_p\}$

SelectBestResponse$(p, a_{-p})$
$a_p \leftarrow x^{\text{best}}$
end for
If $\|o - a\|^2 < 0.00001$ do $counter \leftarrow counter + 1$
If $(k_1 > BRMINREP$ & $counter > conv)$: break
end for

ALGORITHM 6: SelectBestResponse$(p, a_{-p})$
$EMREP$: number of electromagnetic iterations
$LSREP$: number of local search iterations
$\omega = (\omega_1, \omega_2)$: step length for local search procedure
Generate $T$ random actions $x^t \in \mathcal{A}_p$ for $t \in \{1,2,\dots,T\}$ and calculate $f_p(x^t) \leftarrow \pi_p\left(x^t \middle| \theta^z, a_{-p}\right)$
For $k_2 = 1$ to $EMREP$ do
$x^{\text{best}} \leftarrow \text{argmax}\{f_p(x^t), \forall x^t \in \mathcal{T}\}$
For all $x^t \in \mathcal{T}$ do
Calculate charges $q^t$
$F^t \leftarrow 0$
End for
For all $x^t \in \mathcal{T} \backslash \{x^{\text{best}}\}$ do
For all $x^u \in \mathcal{T}$ do
If $f_p(x^t) < f(x^u)$ do $F^t \leftarrow F^t + \frac{(x^u - x^t) q^t q^u}{\|x^u - x^t\|^2}$
Else $F^t \leftarrow F^t - \frac{(x^u - x^t) q^t q^u}{\|x^u - x^t\|^2}$
End for
End for
For all $x^t \in \mathcal{T} \backslash \{x^{\text{best}}\}$ do
$\eta \leftarrow U(0,1)$
$F^t \leftarrow F^t / \|F^t\|$
For $n = 1$ to 2 do
If $F_n^t > 0$ do $x_n^t \leftarrow x_n^t + \eta F_n^t (u_n - x_n^t)$
Else $x_n^t \leftarrow x_n^t - \eta F_n^t (x_n^t - l_n)$
End for
End for
End for
For all $x^t \in \mathcal{T}$ do
For $k_3 = 1$ to $LSREP$ do
$y \leftarrow x^t$
For $n = 1$ to 2 do
$\kappa \leftarrow U(0,1)$
$y_n \leftarrow y_n + \omega_n (\kappa - 0.5)$
End for

If $f_p(y) > f_p(x^t)$: $x^t \leftarrow y$
End for
End for
$x^{\text{best}} \leftarrow$ argmax $\{f_p(x^t), \forall t\}$

ALGORITHM 7: EvaluateEquilibria()
$MAXDIST$= maximum distance from existing cluster
$MINSUPPORT$= minimum support criterion to avoid local minimum
Vector with number of points per cluster $w = (w^1, \dots, w^R) \in \mathbb{Z}^R \leftarrow 0$
$c_1 \in \mathcal{C} \leftarrow a^1$, $C \leftarrow 1$, $w^1 \leftarrow 1$
For $r = 1$ to $R$ do
$c^{\text{closest}} \leftarrow$ argmin $\left\{\left\|a^r - c^i\right\|^2, \forall c^i \in \mathcal{C}\right\}$
If $\left\|a^r - c^{\text{closest}}\right\|^2 < MAXDIST$ do
$c^i \leftarrow (c^i w^i + a^r)/(w^i + 1)$
$w^i \leftarrow w^i + 1$
Else $c_2 \in \mathcal{C} \leftarrow a^r$, $C \leftarrow C + 1$, $w^C \leftarrow 1$
End if
End for
For $i = 1$ to $C$ do
If $w^i < MINSUPPORT$ do $w^i \leftarrow 0$
Else for $j = 1$ to $C$ do
If $j \neq i$ & $w^j \geq MINSUPPORT$ do
If $(f_p(c_i) < f_p(c^j), \forall p)$ do $w^i \leftarrow 0$
End if
End for
End if
End for
$c^{\text{best}} \leftarrow$ argmax$\{\sum_p f_p(c^i), \forall i$ with $w^i > 0\}$
$o \leftarrow c^{\text{best}}$
BestResponseAlgorithm($c^{\text{best}}$)
If $\left\|o - c^{\text{best}}\right\|^2 > MAXDIST$ print "Cluster is no equilibrium. Further investigation required."

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| $R$ | 10 | $T$ | 5 |
| $BRMINREP$ | 10 | $BRMAXREP$ | 30 |
| $EMREP$ | 4 | $LSREP$ | 30 |
| $\alpha$ | (0.5, 2) | $conv$ | 5 |
| $MAXDIST$ | 5 | $MINSUPPORT$ | 2 |

Table B.1 Algorithm parameters used in the experiment

# Appendix C Additional statistical output

## Chapter 5: ANOVA results[5]

**Analysis of variance table – 2 players**

| | | $\left(i(s_1^{1*})\right)^{Z=2} - \left(i(s_1^{1*})\right)^{Z=1}$ | | | | $\left(m(s_1^{1*})\right)^{Z=2} - \left(m(s_1^{1*})\right)^{Z=1}$ | | | |
|---|---|---|---|---|---|---|---|---|---|
| Variable | Df | Mean Sq | F value | p-value | Sign | Mean Sq | F value | p-value | Sign |
| $\gamma_e$ | 1 | 0.4 | 0.28 | 0.5946 | | 229.7 | 12.03 | 0.0005 | *** |
| $\gamma_i$ | 1 | 12.0 | 8.67 | 0.0033 | *** | 2889.0 | 151.33 | $<2.2*10^{-16}$ | *** |
| $\beta_e$ | 1 | 2.0 | 1.41 | 0.2352 | | 259.8 | 13.61 | 0.0002 | *** |
| $d$ | 1 | 3.5 | 2.54 | 0.1113 | | 65.1 | 3.41 | 0.0650 | * |
| $e_1$ | 1 | 7.4 | 5.35 | 0.0208 | ** | 380.6 | 19.94 | $8.5*10^{-6}$ | *** |
| $e_{-1}$ | 5 | 2.6 | 1.91 | 0.0905 | * | 232.4 | 12.17 | $1.3*10^{-11}$ | *** |
| $\gamma_e * \gamma_i$ | 1 | 3.4 | 2.45 | 0.1178 | | 93.0 | 4.87 | 0.0274 | ** |
| $\gamma_e * \beta_e$ | 1 | 2.8 | 2.05 | 0.1520 | | 0.5 | 0.03 | 0.8688 | |
| $\gamma_e * d$ | 1 | 0.0 | 0.02 | 0.8980 | | 3.3 | 0.18 | 0.6756 | |
| $\gamma_e * e_1$ | 1 | 1.2 | 0.90 | 0.3437 | | 82.5 | 4.32 | 0.0377 | ** |
| $\gamma_e * e_{-1}$ | 5 | 0.8 | 0.60 | 0.6990 | | 12.1 | 0.63 | 0.6760 | |
| $\gamma_i * \beta_e$ | 1 | 7.0 | 5.03 | 0.0250 | ** | 15.9 | 0.83 | 0.3617 | |
| $\gamma_i * d$ | 1 | 3.7 | 2.66 | 0.1033 | | 40.7 | 2.13 | 0.1442 | |
| $\gamma_i * e_1$ | 1 | 13.4 | 9.72 | 0.0019 | *** | 138.8 | 7.27 | 0.0071 | *** |
| $\gamma_i * e_{-1}$ | 5 | 3.4 | 2.49 | 0.0295 | ** | 158.0 | 8.28 | $9.7*10^{-8}$ | *** |
| $\beta_e * d$ | 1 | 4.7 | 3.42 | 0.0645 | * | 14.2 | 0.74 | 0.3889 | |
| $\beta_e * e_1$ | 1 | 4.1 | 2.94 | 0.0867 | * | 11.0 | 0.57 | 0.4488 | |
| $\beta_e * e_{-1}$ | 5 | 4.2 | 3.01 | 0.0104 | ** | 97.7 | 5.12 | 0.0001 | *** |
| $d * e_1$ | 1 | 0.5 | 0.33 | 0.5663 | | 28.3 | 1.48 | 0.2233 | |
| $d * e_{-1}$ | 5 | 1.8 | 1.32 | 0.2539 | | 41.3 | 2.16 | 0.0557 | * |
| $e_1 * e_{-1}$ | 5 | 0.8 | 0.59 | 0.7075 | | 12.6 | 0.66 | 0.6553 | |
| residuals | 1682 | 1.4 | | | | 19.09 | | | |

Table C.1 ANOVA output for the differences in the investment and mark-up choices for the first project in a two-project setting with respect to a single-project setting.

[5] The statistical significance of the results are highlighted as follows: (*) refers to significance at the 10% level, (**) at the 5% level and (***) at the 1% level

**Analysis of variance table – 3 players**

| Variable | Df | $\left(i(s_1^{1*})\right)^{Z=2} - \left(i(s_1^{1*})\right)^{Z=1}$ Mean Sq | F value | p-value | Sign | $\left(m(s_1^{1*})\right)^{Z=2} - \left(m(s_1^{1*})\right)^{Z=1}$ Mean Sq | F value | p-value | Sign |
|---|---|---|---|---|---|---|---|---|---|
| $\gamma_e$ | 1 | 3.4 | 2.70 | 0.1004 | | 11.2 | 0.35 | 0.5536 | |
| $\gamma_i$ | 1 | 17.0 | 13.35 | 0.0003 | *** | 6701.1 | 210.39 | $<2.2*10^{-16}$ | *** |
| $\beta_e$ | 1 | 9.8 | 7.75 | 0.0054 | *** | 222.5 | 6.99 | 0.0082 | ** |
| $d$ | 1 | 11.4 | 9.00 | 0.0027 | *** | 833.3 | 26.16 | $3.2*10^{-7}$ | *** |
| $e_1$ | 1 | 25.1 | 19.80 | $8.8*10^{-6}$ | *** | 229.0 | 7.19 | 0.0073 | ** |
| $e_{-1}$ | 20 | 1.7 | 1.30 | 0.1638 | | 96.2 | 3.02 | $6.6*10^{-6}$ | *** |
| $\gamma_e * \gamma_i$ | 1 | 0.3 | 0.21 | 0.6474 | | 139.8 | 4.39 | 0.0362 | ** |
| $\gamma_e * \beta_e$ | 1 | 0.0 | 0.03 | 0.8551 | | 11.2 | 0.35 | 0.5536 | |
| $\gamma_e * d$ | 1 | 0.8 | 0.60 | 0.4380 | | 102.4 | 3.22 | 0.0730 | * |
| $\gamma_e * e_1$ | 1 | 1.2 | 0.93 | 0.3361 | | 34.5 | 1.08 | 0.2981 | |
| $\gamma_e * e_{-1}$ | 20 | 0.9 | 0.70 | 0.8342 | | 30.9 | 0.97 | 0.4959 | |
| $\gamma_i * \beta_e$ | 1 | 3.3 | 2.61 | 0.1061 | | 32.5 | 1.02 | 0.3121 | |
| $\gamma_i * d$ | 1 | 14.7 | 11.53 | 0.0007 | *** | 0.1 | 0.00 | 0.9522 | |
| $\gamma_i * e_1$ | 1 | 0.0 | 0.01 | 0.9189 | | 1910.3 | 59.98 | $1.1*10^{-14}$ | *** |
| $\gamma_i * e_{-1}$ | 20 | 1.8 | 1.44 | 0.0909 | * | 96.1 | 3.02 | $6.7*10^{-6}$ | *** |
| $\beta_e * d$ | 1 | 0.1 | 0.09 | 0.7595 | | 26.8 | 0.84 | 0.3592 | |
| $\beta_e * e_1$ | 1 | 0.9 | 0.71 | 0.3999 | | 0.1 | 0.00 | 0.9468 | |
| $\beta_e * e_{-1}$ | 20 | 0.8 | 0.61 | 0.9105 | | 32.5 | 1.02 | 0.4334 | |
| $d * e_1$ | 1 | 4.6 | 3.59 | 0.0582 | * | 48.1 | 1.51 | 0.2191 | |
| $d * e_{-1}$ | 20 | 1.6 | 1.28 | 0.1786 | | 93.1 | 2.92 | $1.3*10^{-5}$ | *** |
| $e_1 * e_{-1}$ | 20 | 1.9 | 1.53 | 0.0624 | * | 46.7 | 1.47 | 0.0825 | * |
| residuals | 5912 | 1.3 | | | | 31.9 | | | |

Table C.2 ANOVA output for the differences in the investment and mark-up choices for the first project in a two-project setting with respect to a single-project setting.

## Chapter 6: ANOVA results

**Analysis of variance table – 2 players**

| Response: | | $i(a_1^{*z} \mid \theta^z)$ | | | | $m(a_1^{*z} \mid \theta^z)$ | | | |
|---|---|---|---|---|---|---|---|---|---|
| Variable | Df | Mean Sq | F-value | p-value | Sign | Mean Sq | F-value | p-value | Sign |
| $\gamma_i$ | 1 | 267.2 | 11867 | $<2.2*10^{-16}$ | *** | 1055 | 1510.9 | $<2.2*10^{-16}$ | *** |
| $\gamma_e$ | 1 | 1.151 | 51.12 | $3.4*10^{-12}$ | *** | 521.3 | 746.89 | $<2.2*10^{-16}$ | *** |
| $e_1$ | 1 | 18.54 | 823.56 | $<2.2*10^{-16}$ | *** | 58.99 | 84.519 | $<2.2*10^{-16}$ | *** |
| $e_2$ | 5 | 1.475 | 65.517 | $<2.2*10^{-16}$ | *** | 178.1 | 255.18 | $<2.2*10^{-16}$ | *** |
| $Z$ | 1 | 0.069 | 3.0677 | 0.0805 | * | 132.9 | 190.38 | $<2.2*10^{-16}$ | *** |
| $\gamma_i * \gamma_e$ | 1 | 0.449 | 19.924 | $1.0*10^{-5}$ | *** | 0.58 | 0.8291 | 0.3630 | |
| $\gamma_i * e_1$ | 1 | 8.845 | 392.83 | $<2.2*10^{-16}$ | *** | 1.11 | 1.5936 | 0.2074 | |
| $\gamma_i * e_2$ | 5 | 0.179 | 7.9488 | $3.3*10^{-7}$ | *** | 2.35 | 3.3718 | 0.0053 | *** |
| $\gamma_i * Z$ | 1 | 0.194 | 8.6360 | 0.0035 | *** | 4.43 | 6.3520 | 0.0121 | ** |
| $\gamma_e * e_1$ | 1 | 0.252 | 11.175 | 0.0001 | *** | 173.4 | 248.41 | $<2.2*10^{-16}$ | *** |
| $\gamma_e * e_2$ | 5 | 0.079 | 3.5118 | 0.0040 | ** | 32.84 | 47.046 | $<2.2*10^{-16}$ | *** |
| $\gamma_e * Z$ | 1 | 0.009 | 0.3921 | 0.5315 | | 4.38 | 6.2805 | 0.0126 | ** |
| $e_1 * e_2$ | 5 | 0.027 | 1.2185 | 0.2992 | | 26.29 | 37.666 | $<2.2*10^{-16}$ | *** |
| $e_1 * Z$ | 1 | 0.589 | 26.173 | $4.6*10^{-7}$ | *** | 25.34 | 36.305 | $3.4*10^{-9}$ | *** |
| $e_2 * Z$ | 5 | 0.119 | 5.2837 | $9.8*10^{-5}$ | *** | 14.00 | 20.052 | $<2.2*10^{-16}$ | *** |
| Residuals | 468 | 0.023 | | | | 0.70 | | | |

Table C.3 ANOVA output for the actions in the first project of a $Z$-project pipeline for a player with experience $e_1$ and the opponent's experience level $e_2$ as a factor variable

**Analysis of variance table – 3 players**

| Response: | | $i(a_1^{*z} \mid \theta^z)$ | | | | $m(a_1^{*z} \mid \theta^z)$ | | | |
|---|---|---|---|---|---|---|---|---|---|
| Variable | Df | Mean Sq | F-value | p-value | Sign | Mean Sq | F-value | p-value | Sign |
| $\gamma_i$ | 1 | 167.9 | 5575.5 | $<2.2*10^{-16}$ | *** | 13366 | 3255.1 | $<2.2*10^{-16}$ | *** |
| $\gamma_e$ | 1 | 0.002 | 0.0725 | 0.7877 | | 2057.3 | 501.05 | $<2.2*10^{-16}$ | *** |
| $e_1$ | 1 | 81.29 | 2698.4 | $<2.2*10^{-16}$ | *** | 6482 | 1578.6 | $<2.2*10^{-16}$ | *** |
| $(e_2, e_3)$ | 20 | 2.875 | 95.431 | $<2.2*10^{-16}$ | *** | 53.7 | 13.083 | $<2.2*10^{-16}$ | *** |
| $Z$ | 1 | 0.093 | 3.0858 | 0.0791 | * | 429.7 | 104.64 | $<2.2*10^{-16}$ | *** |
| $\gamma_i * \gamma_e$ | 1 | 0.002 | 0.0649 | 0.7990 | | 3.0 | 0.7243 | 0.3948 | |
| $\gamma_i * e_1$ | 1 | 81.22 | 2696.2 | $<2.2*10^{-16}$ | *** | 301.7 | 73.473 | $<2.2*10^{-16}$ | *** |
| $\gamma_i * (e_2, e_3)$ | 20 | 2.871 | 95.301 | $<2.2*10^{-16}$ | *** | 24.5 | 5.9789 | $1.3*10^{-15}$ | *** |
| $\gamma_i * Z$ | 1 | 0.091 | 3.0308 | 0.0819 | * | 2.9 | 0.7145 | 0.3981 | |
| $\gamma_e * e_1$ | 1 | 0.108 | 3.5908 | 0.0583 | * | 1959 | 477.02 | $<2.2*10^{-16}$ | *** |
| $\gamma_e * (e_2, e_3)$ | 20 | 0.034 | 1.1337 | 0.3065 | | 6.7 | 1.6248 | 0.0395 | ** |
| $\gamma_e * Z$ | 1 | 0.000 | 0.0001 | 0.9920 | | 15.5 | 3.7734 | 0.0522 | * |
| $e_1 * (e_2, e_3)$ | 20 | 0.518 | 17.202 | $<2.2*10^{-16}$ | *** | 90.0 | 21.919 | $<2.2*10^{-16}$ | *** |
| $e_1 * Z$ | 1 | 0.015 | 0.4841 | 0.4867 | | 131.0 | 31.915 | $1.9*10^{-8}$ | *** |
| $(e_2, e_3) * Z$ | 20 | 0.011 | 0.3739 | 0.9947 | | 4.2 | 1.0164 | 0.4384 | *** |
| Residuals | 1905 | 0.030 | | | | 4.1 | | | |

Table C.4 ANOVA output for the actions in the first project of a $Z$-project pipeline for a player with experience $e_1$ and the opponents' experience vector $(e_2, e_3)$ as a factor variable

# Appendix D Laboratory experiment files

## <u>Protocol – Session 3/1</u>

Welcome at this experiment that studies bidding behavior in high-risk projects. This session will last about 2 hours. In a few moments, I will start the experiment and you will all play at the same speed during the entire experiment. This means that everyone will leave at the same time.

The session consists of two parts. In the first part, you will be playing a "low-risk" environment. Each project involves some risk. In order to conquer this risk and in order to make a profit on the project, you will need to make two decisions: an investment decision and a mark-up decision. For the investment decision, you have received a sheet of paper that shows the effect of investing in research. Firstly, research results in a slightly smaller project cost. Secondly, research will give you more certainty about the project cost (so you will be closer to the actual cost of the project). The values on that sheet of paper are expressed as percentages. We will run through some examples to become familiar with the effect and with the characteristics of the normal distribution.

<u>There are experienced and inexperienced players</u>. <u>You will always play against two other players</u>. The computer decides randomly which players are experienced and which players are inexperienced and these roles will be the same during the entire session. Beware, because <u>investment costs money</u>. For each percentage, you will need to pay € 10.000 (while project costs will be around € 1.000.000).

The two parts of this session consist each of 15-25 rounds. <u>The first few rounds are practice rounds</u>. A round runs as follows:

1) You will see a screen with on the left top corner the number of rounds to go. Beneath you will see whether you are an EXPERIENCED or INEXPERIENCED player. That will be the same for the entire game.

2) At the start of each round, you do not know who your competitors are. You can be playing against 2 INEXPERIENCED, 1 INEXPERIENCED and 1 EXPERIENCED player and 2 EXPERIENCED players.
3) You will need to give your preferred investment (between 0 and 5 % and 2 decimals) and your preferred mark-up percentage (between 0 and 50% and 2 decimals). You may enter the same numbers for the different cases or you may apply different choices for each of them. You have approximately 60 seconds to make your decision. So you need to press the "Submit" button when I say "Please, submit your bids now".
4) Now the program will perform some steps in the background:
    a. A cost base is selected for this round and this is the same for each player. The cost base is always around € 1.000.000.
    b. Depending on who your competitors are, your investment and mark-up level are selected.
    c. The computer will shape your normal cost probability distribution based on your investment choice. The average of this distribution is unknown to you, but that will be the actual cost if you win the project.
    d. The program randomly selects a cost estimate based on your distribution. Consequently, you have a 50% probability that your cost estimate is lower than the average and a 50% probability that your cost estimate is higher than the actual cost.
    e. Next, the program will apply the mark-up to your cost estimate. This will result in your bid for the project.
    f. The program will do the same for your competitors. The winner is the one who has submitted the lowest bid.
    g. If you lose, you will lose your investment. If you win, your payoff is calculated as follows: bid you have proposed – actual cost of the project – investment in research.

We will now run through three examples.

A screen will appear with your pay-off calculation. You can write down the output on your answer sheet. First, you indicate who your competitor was in this round. Secondly, you can write the respective investment and mark-up that you have chosen. Afterwards, indicate whether you have won or lost the tender. The program will also show the lowest bid and whether the winner was experienced or inexperienced (you may also note that down on your sheet). Depending on winning or losing, your pay-off will be calculated as described above. You will only have 40 seconds to note down these numbers.

Some things to bear in mind:

- Winning a contract does not necessarily mean that you make a profit;
- Project costs are normally distributed, so there is positive and negative risk;
- In the output screen, only the lowest bid will be reported, not whether the winner of the bid made a profit or a loss;
- You do not know in advance against who you are playing, but you will be randomly matched with other people in the room.

Then, the next round will start and you will be able to enter new investment and mark-up efforts for the different cases. The <u>pay-offs in each round are INDEPENDENT of the pay-offs of the other rounds.</u> That means that pay-offs will not be added up during the game. Afterwards, I will announce that we move on to the second part of the session. In that case, the project cost will be more uncertain (more risk).

At the end of the session, you will be requested to fill out <u>a questionnaire form</u> with your contact details. This is also to calculate your final score. Again, pay-offs will not add up during the entire experiment. Instead, afterwards, we will randomly select 6 rounds to calculate your score in this tournament. You will also receive a sheet of paper to write down in a few lines what your strategy was and why.

I am soon going to start the program and you will see appear the input screen for the first trial round. You will also see what your identity will be in the game (INEXPERIENCED or EXPERIENCED). Because it is a trial, I will give you first 5 minutes to think about your strategy and ask any remaining questions. Also, you have received a form about the informed consent. This experiment has been approved by the KU Leuven ethical commission. So please, also use these 5 minutes to fill this out. Afterwards, there are a few more trial rounds and I will announce when the payment periods will start.

In case of troubles during the experiment, please raise your hand.

We would like to thank you again for your cooperation and let’s hope we get some interesting results.

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